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# Methods for the Prediction and Specification of Functionally Graded Multi-Grain Responsive Timber Composites

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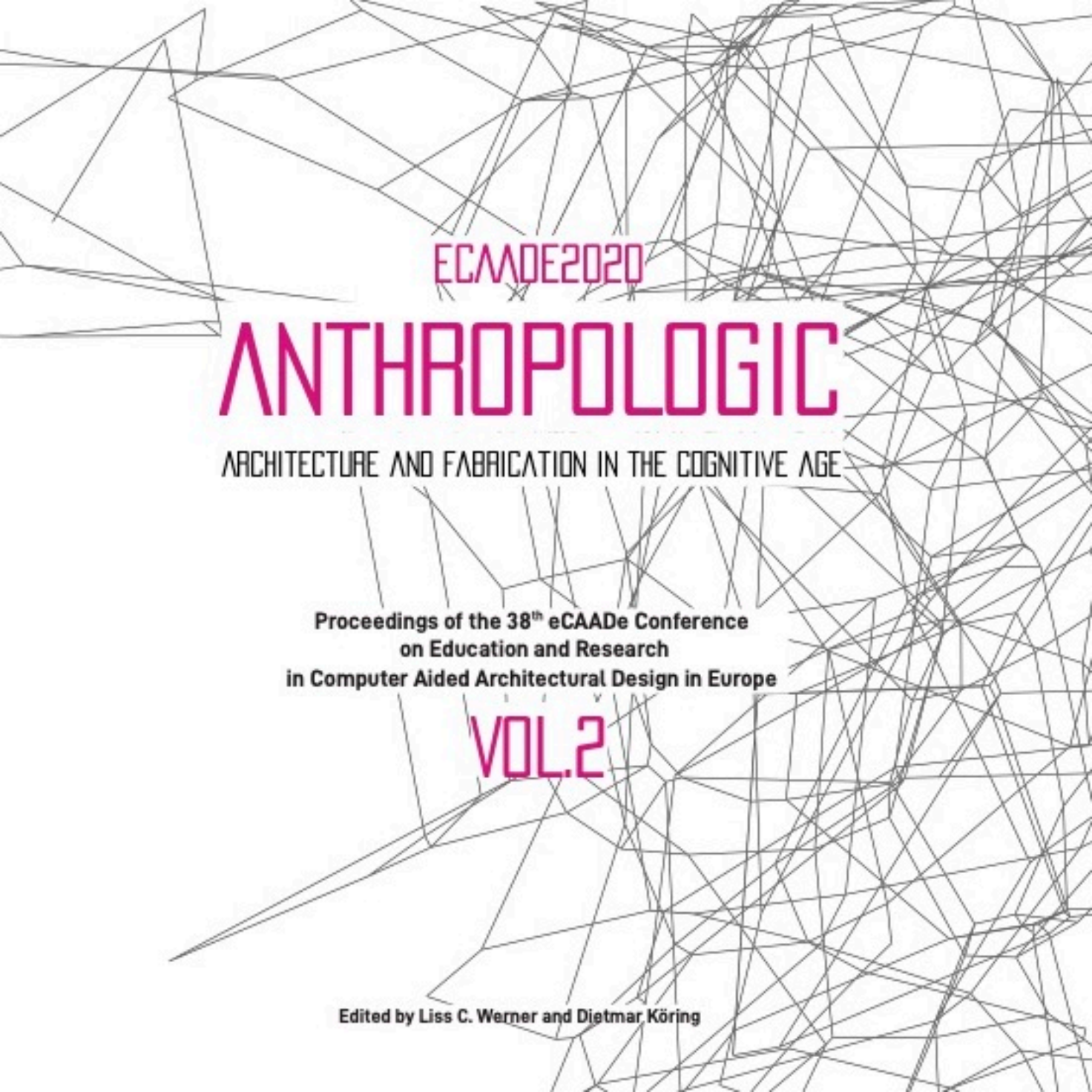
ECAADE2020
ANTHROPOLOGIC
ARCHITECTURE AND FABRICATION IN THE COGNITIVE AGE
Proceedings of the 38th eCAADe Conference
on Education and Research
in Computer Aided Architectural Design in Europe
VOL.2
Edited by Liss C. Werner and Dietmar Köring

# eCAADe 2020

# Anthropologic

# - Architecture and Fabrication

# in the cognitive age

**Volume 2**

**Editors**
Liss C. Werner, Institute of Architecture, Technische Universität Berlin, Berlin
Dietmar Koering, Arphenotype, Cologne

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# eCAADe 2020

# Anthropologic

# - Architecture and Fabrication in the cognitive age

## Volume 2

**Proceedings**

The 38th Conference on Education and Research in Computer Aided Architectural Design in Europe

**Online Conference**
16th-17th September 2020
Berlin, Germany
Institute of Architecture
Technische Universität Berlin

**Edited by**
Liss C. Werner
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# PREFACE

This is the second volume, of two, of the Proceedings of the 38th eCAADe, held as an online event, from 16-17 September 2020 at the Institute of Architecture, Technische Universität Berlin, in Germany. The two volumes together contain the 144 accepted papers. All papers are also available digitally at CumInCAD (Cumulative Index of Computer Aided Architectural Design) – http://papers.cumincad.org

## Theme

> "So architecture, in short, has the capacity to both extend man's destruction of the environment, but also, at its best but much more rarely, it retains the capacity to invent new modes of co-existence, more sustainable ways of living and more aesthetic experiences of inhabitation."
> *Elizabeth Grosz*
> *in Conversation with H. Davis and E.Turpin*

## Context

Humans and technology today form an inseparable link that have profound implications for Earth's ecosystems – leading to the debate for a new era: the Anthropologic. In recent years, the transition from analog to digital architecture has materialized through increasing availability of novel software and new methods in digital architecture fabrication – tooling. The cognitive and digital turn implies ubiquitous computing, artificial intelligence, augmented reality and material intelligence, but to mention a few. The resulting design strategies overwhelm our discipline of architecture, encouraging a re-thinking of architecture, the architect's role and responsibility, as well as architectural education. The development of digital technologies is compounding the need to develop ethics for this new technological state – shifting computer architecture from its focus on technology to a focus on humans.

## Objectives

The theme "Anthropologic – Architecture and Fabrication in the cognitive age … from smart to behavioral … from digital to material", critically questions the idea of the digital as purely technical interface, but encourages the extension of the digital towards, or rather back, to the material world. During the conference we are aiming at reflecting architecture in its transformation – in light of the Anthropocene stipulating data-based strategies for lean automated processes for architecture production and design through big data. eCAADe2020 also focuses on technical solutions fostering ethical feedback into architectonic culture, an evolution of the human-machine interface, ubiquitous computing and machine learning.

Observing mankind and its contribution to the Anthropocene shows that the world is changing and that architects have to adapt to these new circumstances. The discipline of architecture cannot remain indifferent. With digital technologies, artificial intelligence and the internet of things at the core of the emerging paradigm, the 2020 eCAADe online conference has become a preferred place to foster a broad discussion about the place and role of architecture in the proposed geological epoch of the Anthropocene. When we look at Elizabeth Grosz's quote, we also believe that architects need to establish new ways of co-existence with algorithms that should be based on more sustainable ways of life. Even if artificial intelligence needs to be discussed, the goal of overcoming it should be to combat climate change. For this reason, we have invited researchers, professors, specialists and students to discuss topics such as:

- *Design and computation of urban and local systems – XS to XL*
- *Digital perception of Space – Cyber–physical Systems (VR, AR) – design strategies*
- *Health and materials in architecture and cities*
- *Education and digital theory – ethics, cybernetics, feedback, theory*
- *Making through code – built by data and the architectural illustration*
- *Robotic tectonics, automation and interaction*
- *The cognitive city (AI)*
- *Culture/Shift through ubiquitous computing / scripting and lingua franca*
- *BioData/BioTectonics for architectural design*
- *Cognizant Architecture – what if buildings could think?*

*Design and computation of urban and local systems – XS to XL*
Computation in architecture and urban matters is the key objective, as it allows us to shift to design systems rather than buildings. We exchange views on generative design concepts and strategies, shape grammar matters in all scales. How will virtual city modeling and GIS assist our design tool generation process and model manipulation in local systems?

*Digital perception of Space – Cyber–physical Systems (VR, AR) – design strategies*
A track that entitles interactive, virtual and augmented environments, human-building interaction through sensors and their design approaches. We explore the interdisciplinarity of sensor-enhanced material intelligence through physical installations and/or prototypes in order to closely tie human-machine to digital-material.

*Health and materials in architecture and cities*
Health stands for well-being. Well-being is increasingly integrated into architectural simulation and the emission-aware digital planning and physical architectural practice and experimental prototyping. Topics include efforts to balance human needs with environmental viability and digital solutions for sustainable environments, and small-scale systems alike.

*Education and digital theory – ethics, cybernetics, feedback, theory*
Topics will include general CAAD education through the lens of educational institutions and host sessions and discussions covering how to teach digital studios, develop smart design and teaching tools. We touch upon collaborative design, evaluating and theoretical research contributions in the digital turn.

*Making through code – built by data and the architectural illustration*
Can algorithms generate buildings or even architecture? Is a code the new architectural plan? Explore generative design, parametric design, digital design tools and data-driven geometries. Sessions will additionally contain design optimization, simulation, machine learning and Building Information Modeling techniques and experimental hacking.

*Robotic tectonics, automation and interaction*
We dive into digital fabrication, automated digital workflows and discuss associations with scale and materials. 'Coboting' as human-robot collaboration will be central to all our future design and architectural production questions.

*The cognitive city (AI)*
In the age of big data and cloud computing, the city becomes a conscious body that can perceive, sense, filter, identify according to our functions. Artificial Intelligence in the built environment, smart city concepts, simulated behavior will aid us in high-performance analytics and novel responsive surroundings. Let's get lost in between the virtual and the physical capabilities of the city.

*Culture/Shift through ubiquitous computing / scripting and lingua franca*
On one side, this track contains dialogues about information technology and AI in cultural heritage, preservation and sustainability. On the other side, it considers computation and coding as a new drawing skill. Can we link data analytics and scripting as international languages to the power to rule well-adjusted design and making?

*BioData/BioTectonics for architectural design*
Nature as an inspirer will be perpetual to design thinking. We contextualize biological existence, behavior and growth in simulation and design solutions set and train intelligent systems. This track pivots between nature and man-made responsive, growing materials and applications in the built environment.

*Cognizant Architecture – what if buildings could think?*
The Internet of Things, but more so the Internet of Buildings affects our design strategies to create ever-learning and self-enhancing buildings. In this session, we dive into dynamic design solutions, a multi-state system that we aim to give over control to the building itself through the implementation of machine learning. We touch upon material responsiveness and the impact on personal user comfort through real time feedback in building components.

Liss C. Werner and Dietmar Koering
*eCAADe 2020 Conference Chair* and Co-Chair

# WELCOME FROM THE DIRECTOR
# Institute of Architecture, Technische Universität Berlin

Dear colleagues and friends of eCAADe,

The Institute of Architecture (IfA) at Technische Universität Berlin is honoured to host the 38th eCAADe–Education and research in Computer Aided Architectural Design in Europe–in 2020. We are committed to excellence in teaching and research. This obligation arises from the thought that architecture is a cultural technique by which we can create habitats that are beautiful and functional to live in and with, sustainable, forward-looking and building upon the past. We understand architecture as designing for the complex areas of life to reach beyond built objects or clusters of buildings. The institute of architecture understands its role in transferring, embedding, and unfolding science and technology into culturally effective and material environments. We are pleased that almost 1100 students are studying with us each year to ambitiously and courageously tackle present and future challenges through architecture in practice, research and education.

In current times it becomes increasingly visible that digital culture, computational architecture and automated manufacturing have become drivers for our decision-making in architecture and urban design. This evolution has created feedback that encourages us to designing and utilizing novel tools–partially inspired from other disciplines, such as computer sciences or neuro-sciences–for the debate in and the production of architecture, and its forms and functions. *Anthropologic – Architecture and fabrication in the Cognitive Age*, the topic chosen for the conference allows us and you, as researchers, students, practitioners and educators in the field of computational architecture to locate our research, practice and teaching in a paradigm of architectural transformation one hand and human- or rather humanity-focused reflection of architecture on the other. The topic also encourages us, to work and design with the 17 Sustainability Development Goals as set by the United Nations in the Agenda 2030.

The Key Application Areas for science and research that we at TU Berlin have set out for our university are reflected in the 145 papers across 10 tracks, seven keynote contributions and round table discussion presented at the conference and herewith in the very two volumes of the proceedings. Digital Transformation, Energy Systems, Mobility, and Sustainable Resources, Human Health, Humanities and Educational Sciences, Urban Systems and Environmental Systems, Materials, Design and Manufacturing stretch across architectural and urban design, research and education.

We have been challenged with organizing a conference, that will be streamed globally rather than taking place locally in Berlin. The challenge resulted in a comprehensive collection of pre-recorded presentations, a gallery with research results, and, first and foremost world-wide open access to a wide range of excellent research contributions in the field. I would like to thank all involved in arranging, organizing and orchestrating the 38th eCAADe, thriving the *Anthropologic – Architecture and Fabrication in the cognitive age … from smart to behavioral … from digital to material.*

Prof Dr. Philipp Misselwitz
Managing Director Institute for Architecture Technische Universität Berlin

# FOREWORD - eCAADe

Dear eCAADe friends,

The Berlin 2020 virtual eCAADe conference invites 'academicians, researchers, professionals and students to address how problem-formations in architecture, will be defined within the condition of the Anthropocene, that is necessarily multi-disciplinary.
This year, our community was exited to meet with this challenging conference theme in city of Berlin for the 38th eCAADe conference in Europe. However, with rise of global crises, due to Covid outbreak, we all come to terms with the serious adjustments necessary in our ways of engaging during this crisis. The eCAADe council acted fast, by organizing interim meetings in spring 2020 in collaboration with Berlin conference organizers about how to handle 2020 Berlin conference in this global crisis. A joint decision was made to move the 2020 eCAADe Berlin conference and PhD workshops from physical to virtual. eCAADe 2020 Berlin conference is the first virtual eCAADe conference emerged due to the necessity of a global crisis. Nobody, including Berlin team has been prepared for this situation therefore, the eCAADe council made a decision to support Berlin conference organizers with a conference task force composed of eCAADe council members.

I cannot say enough about the deep spirit of cooperation and generosity that has been demonstrated by eCAADe council members and Berlin conference organizers over the past several months. There was a shared strength and commitment that give a life to the eCAADe 2020 Virtual Berlin Conference.
The 2019 eCAADe Porto conference was a unique joint conference organized by two regionally rooted associations eCAADe and SIGradi and was an opportunity to celebrate the idea of togetherness and collaboration. This idea has been expanded by 2020 Berlin online conference that provided free access to all communities interested in research and advancements in Architectural Design and Computation.
The 2020 eCAADe Online Berlin PhD workshop is linked to "Sister Organizations World PhD Workshop" that will be held online at 7th-8th-9th of December. This workshop is the continuation of the idea of togetherness and collaboration that was operationalized at the 2019 Porto conference. The idea was pursued by president emeritus Tadeja Zupançiç in her presidency of eCAADe. As strong supporter of an idea, I initiated the new idea of "Sister

Organizations World PhD Workshop" that aims to build collaboration among young researchers of sister organizations of ACADIA, SiGradi, CAADRIA, ASCAD and eCAADe. The joint world PhD workshop idea was accepted by all sister organizations boards. This workshop will provide an opportunity for young researchers of our communities to collaborate, to experience how PhD studies are conducted in various schools across the world, and gives an opportunity to meet with prominent researchers in the Architecture and Computing field and also situate their study within the word PhD research arena.

eCAADe 2020 Berlin Online conference *"aims to reflect architecture in its transformation during the era of Anthropocene, stipulating data-based strategies for lean automated processes for architecture production and design through big data."* In the era Anthropocene, the education and practice of architecture must represent a different approach, one of coexistence and symbiosis with the biosphere. It must point out new strategies and paths for design and construction that are regulated by environmental needs. Architecture can produce new constructions that transform trajectories of thought; by developing affinities and collaborations through multi-disciplinary, multi-scalar, and multi-centered approaches and use its unique capacity to transform the present and future condition of the Earth System. eCAADe conference is a unique environment for transforming trajectories of thought by providing platforms for multi-disciplinary knowledge sharing. I am looking forward to discussing these new trajectories of thought in virtual Berlin conference that will be open to all interested.

I would like to thank all people who made eCAADe 2020 Online Berlin event possible in this hard time of a global crisis. Especially, to Liss C. Werner, and Dietmar Köring for their excellent organizational efforts. I am grateful to eCAADe Berlin conference task force members: Henri Achten, Bob Martens, Jose Pinto Duarte, Rudi Souffs, Anetta Kepczynska-Walczak, Joachim Kieferle, Gabriel Wurzer, and Tadeja Zupančič, for their support and constructive feedback. I am also grateful to the presidents of ACADIA: Kathy Velikov, SiGradi: David M. Sperling, CAADRİA: Christiane Margerita Herr, ASCAD: Aghlab Alattili for their support of Sister organizations world PhD workshop.

Birgül Çolakoğlu
*President of eCAADe*

# **FOREWORD -** The 10th eCAADe PhD Workshop

*'Each year eCAADe invites applications from young researchers studying in Europe to submit their approved PhD proposal for the eCAADe Grant. Successful applicants attend a pre-conference PhD workshop where they present and discuss their work with experienced colleagues. The grant consists of a subsidy of 400 Euro to cover travel expenses and a special students registration to attend the conference afterwards. The workshop is valuable for PhD students in the earlier stages of the work and NOT mainly intended to be a presentation of an already finished PhD.' http://ecaade.org/conference/grant/*

The first workshop was organized in 2011 in Ljubljana. The initiative derives from the idea to invite the young generation of researchers to the eCAADe community. The tradition was developed by Wolfgang Dokonal and strongly supported by Antonio Fioravanti, both long-standing eCAADe council members.

Due to the uncertainty of the COVID-19 situation the eCAADe council has decided not to skip the opportunity in 2020 but to shift the eCAADe PhD workshop to the online environment. This time no travel support is needed. We are aware that the PhD training needs a continuous personal support rhythm. We are also aware that the online setting requires essential organisational changes. The online environment also requires some additional preparatory steps. To accomplish that a larger task-force consisting of some eCAADe council members has been assigned for this opportunity: Henri Achten,Antonio Fioravanti, Aulikki Herneoja, Anetta Kępczyńska-Walczak, Rudi Stouffs and Tadeja Zupančič. The online PhD workshop offers joint testing of the digital ecologies for the PhD research-in-progress discussions in architectural computing. It offers intensive training of new skills for our selected PhD candidates and for all the actors involved. The usual presentation-and-discussion sequence can change: the presentations can be posted online in advance for the panel members and the audience, so that the joint event can more effectively focus on the discussion. The usual questions from the panel members can be replaced or combined by the questions from the candidate's side.

The young researchers are encouraged to rethink the advantage of virtually inviting the audience to their own research environment, that people can immediately immerse into their worlds and into the moment of their initial research stage in the wider picture of their PhD research.

The PhD research of this year's applicants shows the diversity of the young generation's interests: from BIM, generative design, digital fabrication and feasibility studies to wider issues of adaptable design and building systems, spatial experience and perception as well as architectural education for sustainable design.

The eCAADe online PhD workshop is linked with the CA2RE network - Community for Artistic and Architectural Research - and with the CA2RE+ project - Collective Evaluation of Design Driven Doctoral Training. It builds on their joint online 'Trondheim 2020' event experience in June 2020. The CA2RE/ CA2RE+ setting is a meeting place of the European associations ARENA - Architectural Research European Network Association, EAAE - European Association for Architectural Education and ELIA - European League of Institutes of the Arts. The online PhD workshop initiative opens new opportunities of networking at the doctoral research level in this context. Last but not least, it opens new links with our sister organisations: ACADIA, SigRAdi, CAADRIA and ASCAAD.

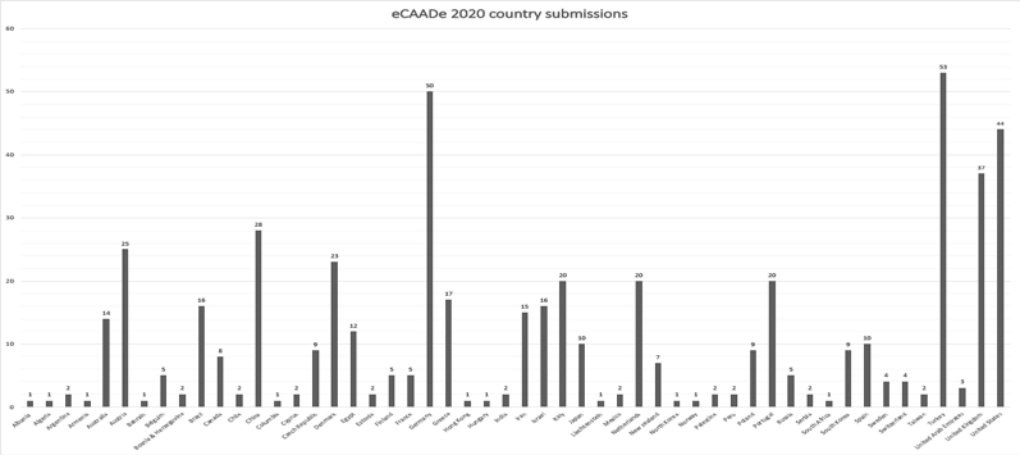
Tadeja Zupančič
*eCAADe Vice President Emeritus*
*2020 eCAADE PhD Workshop Group*

# ON THE eCAADe ONLINE CONFERENCE 2020

The eCAADe 2020 conference in Berlin is taking place as an online event for the first time due to the special circumstances of COVID-19. We have chosen to move eCAADe2020 online, to ensure continuity in the academic and scientific knowledge transfer of the eCAADe community through the conference and the annually published proceedings. The other option would have been to cancel the event. An option that would not have been fair to all authors who submitted wonderful abstracts from around the world. Perhaps the philosopher Markus Gabriel rightly noticed that something invisible has made the weaknesses of our system visible, which speaks to the need for change or at least the need for a new awareness of our relationship with the biosphere. Yet it is a sign to remember how fragile human systems can be in the Anthropocene and that we always have to remember that we as human beings always act as a system with a strong connection to our environment - hence the debate about Anthropologic – Architecture and Fabrication in the cognitive age … From smart to behavioral … From digital to material is relevant and urgent in present times.

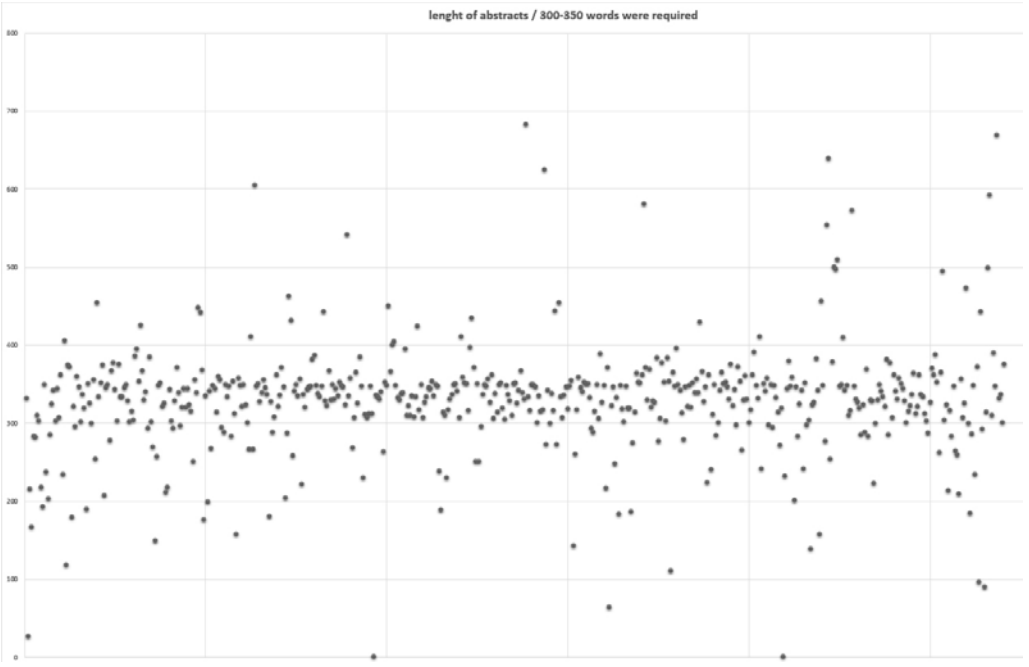
## Development

The topic of the eCAADe2020 in Berlin sparked immense curiosity and interest globally. With the eCAADe2020, a new double-peer review system was introduced, in which all interested parties first had to submit a short abstract between 300 and 350 words plus references. As a result, we received **542** abstracts from **52** countries.




**Call for Papers results – submissions / country**

Abstracts were checked in accordance to the formal quality measures set out for submissions by eCAADe. Each submission had to be strictly anonymous and avoid any hint to the authors' institutional affiliation. Some Abstracts had 0-10 words, other up to 800 words. The majority of abstracts had between 300-380 words. Abstracts, which were far out of scope, were rejected and did not forward to the reviewers. Forwarded abstracts were evaluated by three reviewers not affiliated to the authors to avoid a conflict of interest. **452 abstracts** passed the quality check and were forwarded to the first round of double-blind peer reviewing process. Thanks to eCAADe, we could use the *OpenConf system* to carefully manage the entire anonymous submission and evaluation process.




**Length of submitted Abstracts – 300 to 350 words were required**

Reviewing such large number of abstracts was only possible with the professional and generous support of our Scientific Committee composed by **157** reviewers who accomplished a total of 2199 required reviews. The first stage of the blind-peer review process of the abstracts resulted in a selection of **281 abstracts**, of which authors where invited to submit a full paper for the second stage of the double blind-peer review process. **177 full papers** were accepted through the second stage. We assume that 33 papers were not elaborated further, because due to the "lock-down" of the virus COVID-19, many did not have access to universities and laboratories. In order to minimize the impact, deadlines were extended to accommodate the researchers as much as possible under these conditions. A final number of **144 full papers** could be identified by the scientific committee of eCAADe 2020 and authors were invited to submit camera-ready papers, which you find in volume 1 and volume 2 of the proceedings, as well as online on Cumincad.

## Conference

The eCAADe 2020 conference was held online, hosted by the Institute of Architecture, Technische Universität Berlin from 16.-17. September 2020. Thus, an exact number of participants and attendees could not be identified at the time of preparing the proceedings. The eleven tracks were structured in 21 sessions, that unfolded in three parallel sessions over the course of two days. Our registration system allowed registrants to register for individual sessions and thus create a personalized conference schedule. We thank TU Berlin for the support of utilizing Cisco Webex.
Such structure is also reflected in the organization of the current publication, where each volume is matching each Conference day. Apart from short and crisp presentations of the key thoughts of each paper, we invited authors to submit 10 images of their work for a pre-recorded presentation of 5-7 minutes.

We took the opportunity to invite eight keynote speakers. The seven Keynotes were invited to provide specific, but complementary, visions addressing the spirit and theme of the event.

Due to the Covid-19 restrictions one part of the speakers could be physically present in Berlin during the conference days, the other part was tuned in through a live stream. In order to orchestrate lively input from our keynote speakers we arranged the sessions in a mix of talks and round table discussions.

Thus, we were grateful to count with:

- Prof. Rachel Amstrong
- Prof. Sigrid Brell-Cokcan
- Prof. Michael Hensel
- Lars Krueckeberg
- Prof. Kas Oosterhuis
- Thomas Spiegelhalter
- Prof.em. Chris J.K. Williams

Aside with the Conference sessions, a series of special social programs were cancelled, as we had to organize the conference online. Any 'physical' meetings would not be possible under any health and safety regulations. These 'special' conditions enabled us to develop a standard format for online conferences - which is free of charge for attendants.

We organized an online 'bar', named: Mos Eisley, as a place for academic and non-academic exchange. At Mos Eisley, we have an online stage, which was performed by FESS, a DJ, production and live performance duo from Poland founded by Maciej Kosmalski and Damian Szkatulski and by Jeremy Ham & Jazz (Radio: 3PBS FM - Spaces within space). VR visuals have been created by Uwe Woessner.

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Berlin, September 2020,
Liss C. Werner and Dietmar Koering
*eCAADe 2020 Conference Chair and Co-Chair*

# ACKNOWLEDGMENTS

Our first thanks go to all the authors of the papers who were featured in the current online conference, meeting and roundtable chairs, keynotes, the tutors of the technical workshop and the organizers of the joint PhD workshop, whose role in the success of this ambitious initiative was crucial. Especially under the current pandemic situation - without their support, eCAADe2020 would not have been possible. Many thanks also to the international scientific committee and the reviewer, who evaluated the 541 abstracts and the 177 complete papers. This demanding task was only accomplished thanks to eCAADe for access to the OpenConf system, Martin Winchester for support in the collaboration, Gabriel Wurzer, Wolfgang Lorenz, Martin Baier and Theresa Lohse from the ProceeDings team for the successful production of this extensive publication to Bob Martens for the CumInCAD integration.

This years' eCAADe Online Conference would not have been possible without the commitment of the eCAADe COVID-19 Task Force and the President, Birgul Colak, and the Council Members. We thank them for embracing the challenge to make the eCAADe2020 happen, due the difficult pandemic circumstances and trusting our team to make it reality. It is never enough to remind the decisive support we got from the Joint Committee members who kindly shared with us their experience and recommendations.

At Technische Universität Berlin, we are thankful to Prof. Dr. Philipp Misselwitz, Director of the Institute of Architecture, Prof. Jörg Stollmann, Study Dean, and Prof. Raoul Bunschoten, chair of Sustainable urban Design and Planning, who supported hosting the event at the School throughout preparation time. We also want to express our gratitude for their invaluable help and generous time to our local team and the staff at TU Berlin, in particular, to our students and research support team Louna Al Bondakji, Martin C. Baier, Tunca Beril Basaran, Esra Cuemert, Jennifer Jiang, Valmir Kastrati, Theresa Lohse, Suryaveer Patnaik, Amirhossein Rezaeicherati and Sebastian von Stosch. Special thanks go to the IT Administrative and Support Team of the TU Berlin: Peter Fischer, Carmen Preuß, and Arthur Schmock.

A final word to acknowledge our sponsors Bentley Institute, Deutsche Forschungsgemeinschaft DFG, Gesellschaft von Freunden der Technischen Universität Berlin e.V., Biomimetics mdpi publishers, CyPhyLab, and our host Technical University Berlin, Institute of Architecture.

Berlin, September 2020,
Liss C. Werner and Dietmar Koering
*eCAADe 2020 Conference Chair and Co-Chairir*

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## eCAADe

**www.ecaade.org**

eCAADe (Education and Research in Computer Aided Architectural Design in Europe) is a non-profit making association of institutions and individuals with a common interest in promoting good practice and sharing information to the use of computers in education and research in architecture and related professions. The organization was founded in 1983, and organizes an annual conference, which is hosted by a different member University each year.

## CumInCAD

**http://papers.cumincad.papers.org/**

eCAADe initiated and manages the very successful CumInCAD archive of research publications in the field of Computer Aided Architectural Design. CumInCAD is a valuable resource for researchers, educators and others in the field. eCAADe has also collaborated with sibling associations to create the International Journal of Architectural Computing (IJAC).

**Sibling Associations**

ACADIA
CAADRIA
SIGradi
ASCAAD
CAAD Futures

# KEYNOTES

## Chris Williams

*Keynote: Anthropology and computers - is it possible not to be depressed in the age of multinationals?*

Chris joined Ted Happold's group at Arup in 1972 where he worked on Frei Otto's Multihalle gridshell in Mannheim. His research interests hinge on the relationship between geometry and structural action as applied to towers, bridges and tension and shell structures. His work in the generation of structural form through biological and other analogies has led to collaboration on projects including the British Museum Great Court Roof, the Savill Building, the Gardens by the Bay glasshouses and the Netherlands Maritime Museum. His work on these projects involved writing project specific software for geometry definition and structural analysis.

## Michael Hensel

*Keynote:* En route to Embedded Architectures and why anthropological inquiry can no longer be anthropocentric

Michael Ulrich Hensel is a German architect, researcher, educator and writer. His main areas of interest are "performance-oriented Design" and "Performance-oriented Architecture". Hensel has been a key proponent of interdisciplinary research by design in architecture since the mid-1990s, founding and current chairman of OCEAN Design Research Association and SEA – Sustainable Environment Association. He is a prolific writer whose work has been published world-wide. Since 2018 he is professor at TU Wien where he heads the department for digital architecture and planning and where he serves as a board member of GCD the Center for Geometry and Computational Design.

## Lars Krückeberg

*Keynote:* EVIDENCE BASED DESIGN. How algorithms and good architecture can heal.

Lars Krückeberg studied architecture at the Technical University Braunschweig, Germany, the Università degli Studi di Firenze, Italy, and the German Institute for History of Art, Firenze, Italy. He graduated as Dipl.-Ing. Arch. in Braunschweig and received his Master of Architecture at the Southern Californian Institute of Architecture SCI Arc, Los Angeles, USA. After visiting professorships at HafenCity University in Hamburg and the RWTH Aachen, Lars Krückeberg has been a visiting professor at the TU Delft in 2017/18. In 1998 Lars Krückeberg established GRAFT in Los Angeles together with Wolfram Putz and Thomas Willemeit. With further offices in Berlin and Beijing, GRAFT has been commissioned to design and manage a wide range of projects. GRAFT has won numerous national and international awards and earned international reputation throughout its existence.Since 2015 GRAFT offers sustainable housing systems in modular design in order to quickly construct accommodations for refugees. The company called Heimat2 was founded together with three other companies working in project development and communication

## Rachel Armstrong

*Keynote: Natural computing: return of the Analogue*

Rachel Armstrong is Professor of Experimental Architecture at the School of Architecture, Planning and Landscape, Newcastle University. Her work explores how our buildings can incorporate some of the properties of living systems to become 'living architectures'. She was coordinator for the FET Open Living Architecture project (April 2016 – June 2019) and coordinates the EU Innovation Fund ALICE project. She is a Rising Waters II Fellow with the Robert Rauschenberg Foundation (April – May 2016) and a 2010 Senior TED Fellow. She is also a Member of the Hub for Biotechnology in the Built Environment at Newcastle University and Director and founder of the Experimental Architecture Group (EAG) whose work has been published and exhibited internationally.

## Thomas Spiegelhalter

*Keynote:* Disruptive AI Data-Driven, Carbon-Positive, Bio-Inspired Optimization Design Workflows, 2020-2100

Thomas has performed design and built research in Europe, the Americas, Asia, Africa, and the U.S. on numerous solar, carbon-neutral, zero-fossil-energy, and passive architectural projects; large-scale master planning and post-industrial infrastructures, landscapes, and engineered suspension bridges. As a result of his 30 years of awarded designs and built work, consulting, research, and teaching, Spiegelhalter has received 54 prizes, awards, and honours in competitions individually and in collaboration with engineers. His research work as a Professor at FIU involves geospatial and climatic data repositories with AI data-driven generative design workflows, mostly BIM-Dynamo-Grasshopper coding with biomimetics. The current CRUNCH research (http://crunch.fiu.edu/) is focused on optimized building and city design fitness tests towards carbon-neutrality on a timeline from 2020 to 2100.

## Sigrid Brell-Cokcan

*Keynote: Internet of Construction*

Sigrid Brell-Cokcan is the founder and director of the new Chair of Individualized Production at RWTH Aachen University and co-founded the Association for Robots in Architecture in 2010 together with Johannes Braumann. IP focusses on the use of innovative machinery in material and building production. In order to create an environment that allows the efficient, individualized production of lot size one, new and user friendly methods for man machine interaction are developed. The Chair of IP employs researchers from different fields of robotics and building production to streamline the necessary digital workflow from the initial design to the production process; shaping the construction site of the future via intuitive, easy-to-use interfaces. She holds a Doctorate in technical sciences from TU Vienna (2014), a Master in Architecture (1998) from the Academy of Fine Arts Vienna (honoured with Carl Appel Prize), is a member of the Austrian Chamber of Architects and has completed international studies in architecture at University of Sydney (1994).

## Kas Oosterhuis

*Keynote:* Interactive and Pro-active Environments | Participatory Design Instruments

Professor Kas Oosterhuis is both a visionary and a practicing designer, leading the innovation studio ONL and the Hyperbody research group at the TU Delft. Environments at all scales – from furniture to buildings to cities - are considered complex adaptive systems, both in terms of their complex geometry and their behavior in time. The main focus of the current research is on parametric design and robotic building in all phases of the design to production and the design to operation process. Projects like the A2 COCKPIT building in Utrecht, the BÁLNA mixed use cultural center in Budapest, the LIWA tower in Abu Dhabi and the individually customizable BODY CHAIR are living proof of Oosterhuis' lean design to production approach, in terms of precision, assembly time, sustainability, costs, and above all by his design signature Oosterhuis' built projects are characterized by a strong integration of structure, skin and ornamentation.

# TECHNICAL ONLINE WORKSHOPS

## TRACK 1:

## DESIGN AND COMPUTATION OF URBAN AND LOCAL SYSTEMS – XS TO XL

### MACHINE LEARNING FOR URBANITY

*Zvonko Vugreshek (BTU Cottbus-Senftenberg)*

Having the machine take on more decisions than the user has been ever so popular, machine learning is implemented in almost all segments of life nowadays. In the scope of urbanism and urban design, the optimal choice is often quite difficult. There are much more parameters and regulations to be aware of and we are limited as beings to make such complex decisions in a rather short amount of time. This the key point where we introduce machine learning, to help people make better decisions and thus reducing their potential errors. Starting from choosing the perfect plot to build upon and then building up through automated choices until we reach to the end where we would have an optimal urban scenario to put our design intent into. This workshop took participants through single\multi objective optimization, regressions, clustering and then utilizing some neural network autoencoders to accurately predict and define the perfect surrounding for any design intent.

### ADAPTIVE ARCHITECTURE

*Stepan Kukharskiy (SA lab)*

Usually seen as a static form, architecture now faces the dynamism of current life. While older buildings get demolished or sometimes renovated, modern buildings strive to be multifunctional structures, open for different scenarios and needs that life suggests. Adaptive design in architecture today is a way to establish a harmonious connection between buildings, nature and people. We can design new types of architecture, using big data and computational design tools.

Designing new fluid and dynamic buildings and spaces suggests new ways of interaction with them. During the workshop the participants created a web-app for designing adaptive

spaces and structures. The app will become an interface of an architectural project. The goal of creating the app was to allow people to interact with the structure, generate options and suggest new possible ways of its existence.
In the course of this workshop, participants jumped into the basics of web development, learned coding in JavaScript, WebGL technology and Threejs library. The final app was aimed to be hosted online, on glitch.com.

## TRACK 3:
## DIGITAL PERCEPTION OF SPACE – CYBER–PHYSICAL SYSTEMS (VR, AR) – DESIGN STRATEGIES

### ANIMATED URBAN PERCEPTION

*Prof. Giulia Pellegri (Polytechnic School of Engineering and Architecture – University of Genoa)*

The perception of spaces plays an extremely important role in project management. But what does perception mean? How has perception changed with the IT revolution? What are the principles that condition people in perceiving a space as a barrier, as a transition space or even as a non-space? How to communicate the perception of urban and imaginative realities?
The workshop was a study on the schematization and representation of ideas and concepts, mainly in the architectural field through firstly, a theoretical in-depth introduction about the topics and secondly, the practice of concepts in a coworking moment among the participants.
On the example of Berlin and Genoa the participants identified the peculiar perceptual elements and assumed ideal urban transformations immediately shared with animated GIF drawings among the participants. Finally, they produced posters that represent optical illusions capable of eliminating social, territorial, political and psychological barriers.

## TRACK 4: MAKING THROUGH CODE – BUILT BY DATA AND THE ARCHITECTURAL ILLUSTRATION

### BUILDING INSTINCTS

*Ass. Prof. Raimund Krenmueller (Institute for Advanced Architecture of Catalonia)*

In this workshop, neuro-evolution, the use of evolutionary algorithms to determine the parameters of artificial neural networks, was explored as a strategy to develop autonomous behaviors of building machines (i.e. robots).
EVO-NET, a distributed software framework for artificial evolution of neural robot controllers (using the NEAT family of algorithms and the robotics simulator CoppeliaSim) was introduced to the participants and applied to evolve building behaviors of autonomous collective agents.
Participants of this workshop explored neuro-evolution (and its constituent concepts of neural networks and evolutionary algorithms), its potential for architectural design and robotic construction in a learning-by-doing environment, as well as they acquired the skills to incorporate neuro-evolution strategies and simulation tools in their own workflows beyond the duration of the workshop.

## TRACK 7:
## COGNIZANT ARCHITECTURE - WHAT IF BUILDINGS COULD THINK?

### COGNITIVE ASSEMBLAGES

*Alessandro Mintrone (University of Bologna), Alessio Erioli (University of Bologna, Co-de-iT)*

This workshop explored iterative assemblages of discrete parts combined with Machine Learning techniques operating at the decisional level, focusing on the generation of complex and heterogeneous spatial conditions.
Participants worked in Unity3D + TensorFlow, where in one part, participants worked with a custom implementation of the Wave Function Collapse algorithm, a procedural generation algorithm which produces images by arranging a collection of tiles according adjacency and frequencies rules.

In another session, participants were introduced to Machine Learning techniques, in particular to Reinforcement Learning. Using the Unity ML-Agents Toolkit, a Reinforcement Learning library, participants were trained a Neural Network to perform tiles selection during the iterative assemblage aiming at specific spatial qualities (e.g. density, directionality, connectivity).
This was achieved through acquiring a pre-trained network and its parameters, a newly trained Neural Network and how changing the training goal effects the spatial qualities of the aggregation and finally, visualization techniques for image and video production showcasing the spatial qualities of the outcomes while keeping track of the training process with Tensorboard.

**DIGITAL TWIN**

*Maria Gkovedarou (Bentley Systems)*

A digital twin is a digital representation of a physical asset, process or system, which allows us to understand and model its performance. Infrastructure digital twins—iTwins—are advancing BIM by enabling immersive visualization and analytics visibility.
iTwins are emerging now because of a convergence of technologies that enable an immersive and holistic view of infrastructure assets—above and below ground. These include 3D/4D visualization, reality modeling, mixed reality (XR), and geotechnical engineering. This workshop dealt with the digital twin in the construction industry. Digital context on the one hand, and time on the other hand, are two examples of things that are missing in BIM that Bentley brought to the workshop table with their technology of digital twins.

## TRACK 8:
## THE COGNITIVE CITY (AI)

### DYNAMIC CANVAS

*Nilufer Kozikoglu (Tuspa, Urban Atolye)*

Currently, our research on architectural design process-based network thinking is evolving in two platforms: As a grasshopper module and a Unity-based game application. The named tools enabled the participants of the workshops to play and adjust relationships between the variables of a project, mainly spatial and contextual in a very loose metric analogy and access this information to arrive at design decisions as well as evaluate them. The workshop program included a seminar on space syntax, network thinking, graph theory applications and design probing. The design interfaces were introduced, and participants worked on a rubric that is derived out of existing projects organizational layout data and reinterpretations, followed by iterative design sessions with the tools. Finally, the sessions ended with comparative presentations.

The aim of these interfaces was not to arrive at planning the configurational orthographic data, but to enable the architectural sketch session that used to be within the hand/paper realm within the coded computerized environment augmented with a series of evocative chance inclusive visualization potentials.

## TRACK 10:
## ROBOTIC TECTONICS, AUTOMATION AND INTERACTION

### DYNAMIC FACTORY

*Anatolii Kotov (Brandenburg University of Technology)*

In architecture fabrication problems arise from challenging tasks, material complexity and high technical demands from architects and engineers. Here comes the idea of the dynamic factory. What if we could go from a centralized system of a traditional pipeline to decentralized dynamic system of robots, that are self-aware in space, and can change position/function. This leads to functional redundancy and overall stability. The problem of

decentralized self-organizing systems has always been their complexity for humans to observe such complicated dynamic relations between components in the system. In order to try to manually solve such a problem, we can create an observing system based on a neural network to understand if your pipeline is working correctly or not.
The workshop provided a basic understanding of the creation of robotic pipeline able to form/fabricate a simple small architecture or decorative objects. Participants went from simulation on personal devices to full-scale testing in the laboratory equipped with advanced robotics. Several technical aspects of its practical implementation were examined in detail: robot controlling, self-organizing systems, neural network monitoring. The software used: Python, Rhino+Grasshopper, RoboDK, MQTT for networking.

**KUKA CRC \| CLOUD ROBOT CONTROL FOR REMOTE ROBOTICS**

*Ethan Kerber (Chair of Individualized Production RWTH Aachen University & Robots in Architecture Research)*

The Chair for Individualized Production and Robots in Architecture Research have developed a new cloud-based approach to working remotely with robotics: KUKA\|crc. Cloud Robot Control brings industrial access to online collaboration.
The remote robotics framework enables international teams to collaborate with robots even when they cannot be onsite.
During this workshop, participants learned to remotely simulate robotic movements, send programs over the cloud, monitor progress and adapt to inaccuracies in actual material, all while controlling the process from their own international location.
The robotic cell is comprised of a KUKA iiwa collaborative robot capable of force torque sensing. This sense of touch allows for adaptive machine interactions. The robot can feel if it has contact with a surface and adapt its program, enter soft or even safe mode.
Participants monitored their programs' progress in real time through a digital twin as well as multiple video streams. By realizing a new connection between participants and the technology of the robot lab, we prioritized access to learning and technology while pushing online collaboration beyond zoom meetings and into online remote robotic fabrication.

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# D1.T6.S2. BIO DATA /BIO TECTONICS FOR ARCHITECTURAL DESIGN

## *Generative and synthetic biological design imaginations for the Miami bay area*

*Thomas Spiegelhalter[1], Alfredo Andia[2], Juhasz Levente[3], Srikanth Namuduri[4]*
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*In less than 150 years our carbon society transformed the planet. Today more than 50% of ecologies in the world are determined by unsustainable industrialization processes. The latest IPCC reports show that we are quickly arriving at points of no return in the warming of our planet. We cannot afford to continue in the same direction, we need a new imagination. As part of an E.U.-US funded $1.9 million research project we have been working on multiple projects for the future of the Miami islands since 2018:1. We developed a generative GIS-BIM based Python API for mapping and optimization of carbon-neutral design workflows. It includes genetic design combinatorics with intuitive graphical Dynamo-Python-Grasshopper programming with experimental design results. 2. We worked on a series of design research for the Miami Bay that envisions islands, living shorelines, programmable soils, and infrastructures that grow by themselves using synthetic biology.*

**Keywords:** *Automated Workflows, Synthetic Biology, Artificial Intelligence, Architecture, Sea-level Rise*

# Part 1: The Integrated Decision Support System

Part 1 includes the objectives of the E.U. Sustainable Urbanization Global Initiative (SUGI) and the National Science Foundation-funded research project for the Climate Resilient Urban Nexus Choices (CRUNCH) to develop an interactive Integrated Decision Support System (IDSS) app with real-time data processing and scenarios modelling. The ID-DSS is an nd-digital geo-map based platform that allows decision-makers and citizens with different knowledge levels to provide consistent and coordinated support for multiple users on varied decisions. It includes carbon-neutral city analysis, design scenario planning, and AI data-driven optimizations (Figure 1). This first test workflow was developed to calculate the CRUNCH Energy-Water-Food-CO2 Nexus at a municipal level using Rapid Energy Modelling (R.E.M.) techniques to create a baseline calculation from which to consider building optimizations, retrofitting, and renewable energy production in design studio experiments to aid in reaching Carbon-neutral energy outcomes on a baseline of

iterated existing and newly designed city scenarios from 2018 to 2100. The aforementioned automated cloud-based workflows, design research, and synthetic biological investigations are critical to question our imagination on how we can mitigate the effects of sea-level rise, salt-water intrusion, tropical cyclone genesis, extreme precipitation, and increasing latent heat events. The research conclusions will ask what will be a carbon-neutral AI-powered smart infrastructure for coastal cities in 20, 40, or 80 years from now? How synthetic biologically designed and operated urban green-blue building and infrastructures will interact with their ecosystems?

The R.E.M. method does not require lengthy in-depth onsite analysis of individual buildings within a municipality, rather it uses verified international industry standards, meaning real-time measured cloud-based retrieved energy data for building typologies, zonings, schedules, materials and systems, and energy supply mix of the municipalities (Figure 2).

The second test workflow includes understanding the CRUNCH Food, Energy, and Water (FEW) Nexus various parameters such as energy-water-food consumption, population, sea-level rise, storm surge, CO2, etc. were estimated. Also, to assess the opportunities to transition to self-sufficient and carbon-neutral cities, the solar electric and thermal potential was estimated and cross-examined with the first baseline workflow. The focus was on the two cities, namely South Miami and Miami Beach. The estimates and data processing for the online IDSS were made at the census block level.

With the goal of transparency, only open data and free tools were used for the analysis and estimation. The computation was done using Python. QGIS is an open-source tool for working with geographical data that also supports python. Figure 3 is a screenshot of visualizing the energy consumption of South Miami and Miami Beach on QGIS. Pandas and GeoPandas libraries in python were used extensively. Pandas is a library for working with tabular data and GeoPandas is for working with geographical data. Census block shapefiles and population are openly available. Also, Miami Dade County has made 2D building shape information openly available. The building information shared by the county was imported into a platform called OpenStreetMap, which is a volunteer project, similar to Wikipedia but with spatial data and maps. It means that many buildings of the original dataset were updated by volunteers, so it was assumed that it is more detailed and accurate than the county's building data. For example, some demolished buildings have been deleted, newly built ones added. Additionally, in some cases, it also codes the building type. The census block data and building shapes consist of polygonal shapes represented by the latitude and longitude of each vertex. This allowed us to make estimates at a census block level by looking at the building within its boundary.

From the polygonal shapes of each building, the base area can be calculated using existing functions in GeoPandas. The height information was available for about 80% of the buildings and was missing for the rest of them. Since the volume information is required for estimating energy, the missing data needed to be imputed. Machine Learning was applied to estimate the height using the rest of the available parameters as predictors. The python library Sklearn was used for this purpose. For the beta version of the app, a simplifying assumption was made that the energy consumption is proportional to the volume of the building. Also, the city level energy usage was obtained from FPL (Florida Power and Lighting Company). Using this information, the energy usage for each census block was estimated. Water usage was also estimated in a similar fashion, starting with the total usage at the city level. Project Sunroof is an initiative/tool from Google that offers estimates of solar PV potential. Google Earth provides high-resolution imagery of rooftops. Project Sunroof initially used these images to calculate the solar potential of each roof. After the initial estimation phase, Artificial Intelligence was used to predict the solar system's potential. To be specific, the initial estimates were used to train machine learn-

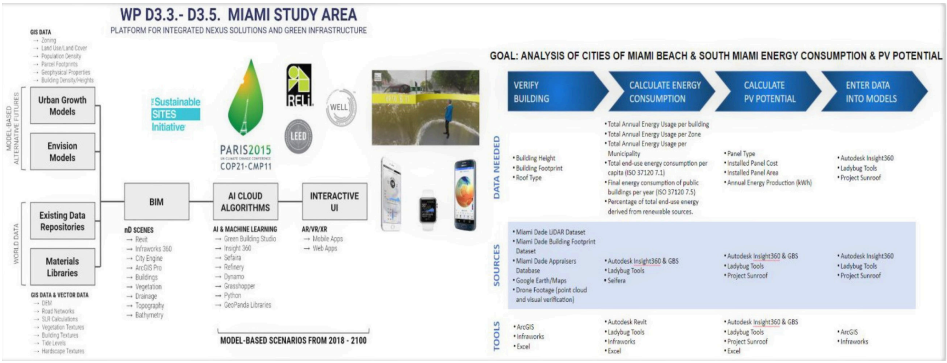


Figure 1
Right and left image; Workflow diagram of the general CRUNCH work deliverables with open source GIS into Autodesk Infraworks, Civil, ESRI ArcGIS Pro, Revit-BIM, Green Building Studio, Insight360, COVE, Dynamo, Grasshopper, Python, GeoPanda, etc. for analyzing, coding, designing, scripting, and optimizations of cities and buildings. This includes design studio scenarios from 2018 to 2020. (FIU CRUNCH PI Thomas Spiegelhalter, Fall 2018 to Spring 2020).

ing models that can predict the solar potential based on the information from Maps and Google Earth. This tool can either provide estimates for each building or for a census tract. The latter was leveraged to obtain solar systems potential for South Miami and Miami Beach at a census tract level and was used to make estimates at a census block level. The weather data is automatically retrieved from National Renewable Energy Laboratory (NREL), utility electricity rates information from Clean Power Research, Federal, State and local authorities as well as relevant utility websites, Solar Renewable Energy Credit (SREC) data from Bloomberg New Energy Finance, SRECTrade, and relevant state authorities, and aggregated and anonymized solar cost data from Aurora Solar software.

## 1.A. IDSS APP DATA AND METHODS

The rate of sea level rise (SLR) is not constant across the globe and it shows great local variations. As a result, adapting for changing water levels and planning has a strong local component and each coastal area must consider their unique characteristics. For example, Wdowinski et al. (2016) shows that the rate of SLR in Southeast Florida is more accelerated than the global average (9 +- 4mm/year vs. 3.2 +- 0.4mm/year) which will likely be manifested in larger social and economic impacts compared to some other parts of the world. In addition to the challenges posed by the rising sea levels, anthropogenic climate change also poses risk to coastal communities by higher storm surges (1) and the co-occurrence of sea level rise, storm surge and flooding caused by heavy precipitation (2). For this reason, it is crucial that we understand the local impacts of climate change. The following sections detail a web-based application that was developed to support decision making in the City of South Miami and Miami Beach.

## 1.B. MODELING INUNDATION LEVELS

A necessary step in modelling inundation levels is to choose a reference surface to which water height or depth is compared to. Tidal datums are locally standardized elevations set to certain phases of the

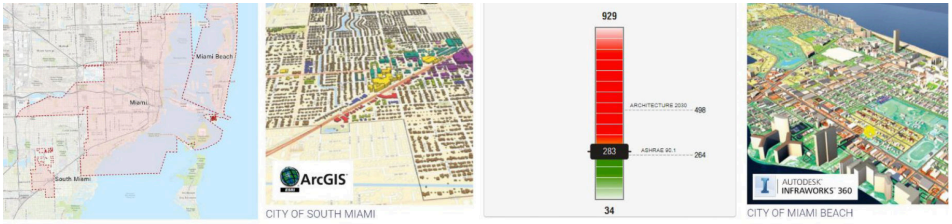


Figure 2
Right and left image; AI data-driven City Carbon-Neutral Design workflows. (CRUNCH PI Th. Spiegelhalter, F 2018-2019).

tide for a certain area with the same oceanographic characteristics. Water levels were measured to the Mean Higher High Water (MHHW) surface, which is the average of the higher high water level. A series of SLR inundation scenarios between 1 ft and 8 ft with 1 ft increments was created using a so-called bathtub model. The digital elevation model (DEM) used in the computations was derived from a 2015 LIDAR dataset of Miami-Dade County given in the NAVD88 vertical datum. This surface is 0.1m below the MHHW in South Florida which was adjusted in the calculations. The methodology is described by Zhang et al. (2011). In addition, relevant structures, such as levees and weirs were also considered to create a hydrologically accurate model. The Sea, Lake and Overland Surges from Hurricanes (SLOSH) model developed by the National Weather Service (NWS) was used to derive storm surge inundations caused by hurricanes category 1 through 5. Due to the uncertainty of modelling, tropical storms are not included in the application. In SLOSH, the Maximum Envelope of High Water (MEOW) shows the maximum likely extent of flooding in a basin for a given storm category with a certain trajectory and forward speed. Our calculations use the MOM (Maximum of MEOWs) output of SLOSH for the Miami basin, which considers multiple combinations of forwarding speed and trajectory for a basin to create a worst-case snapshot for a particular storm category. At a later step, all possible combinations of SLR and storm surge scenarios were created by adding the corresponding inundation layers together (e.g. 2 ft of SLR and storm surge caused by a category 4 hurricane).

## 1.C. ESTIMATING SOCIAL AND ECONOMIC IMPACTS OF SLR AND STORM SURGES

Using a GIS based approach, the social and economic impacts or SLR and storm surge inundation scenarios were estimated in the City of South Miami and Miami Beach using US Census blocks as the spatial unit. Census blocks were found to be sufficiently small in size to capture fine urban structures within these cities. Variables were organized into the following categories: demography, property, facilities, land use and roads. Each category consists of multiple attributes, such as racial breakdown, total assessed property value, total area per land use category, etc. First, inundation scenarios were converted to a binary GIS layer (i.e. area is under water or not), then these were spatially overlaid with the variable in question. As the last step, the affected supply (e.g. population) within a block was estimated in blocks overlapping the inundation extent. This workflow was automated with Python scripts. At the end of this step, the total and affected values for an attribute (e.g. area of residential land use and area of residential land use underwater for a scenario) were available for each block within the study area for each combination scenario.

## 1.D. IDSS WEB APPLICATION

Effectively communicating complex environmental issues to a diverse audience is a challenge. This is especially true for presenting potential impacts of future scenarios. Therefore, our goal was to develop a lightweight and user-friendly web application that dynamically and interactively visualizes the potential social and economic impacts of coastal inundations and parameters related to the food, water and energy nexus for any given area within the City of South Miami and Miami Beach. Free and open-source software has already been used to build interactive web-based GIS applications to model excess waters (4). Our application is built with purely open-source software, which allows cost-effective and rapid development. The application implements a flexible design that allows the addition and removal of additional attributes in later phases of the development (Figure 3).

## 1.E. IDSS SERVING DATA

Two types of data are being visualized in the application: spatial and non-spatial. Non-spatial data consists of the pre-calculated socio-demographic variables and food, water and energy nexus parameters for each block within the study cities.

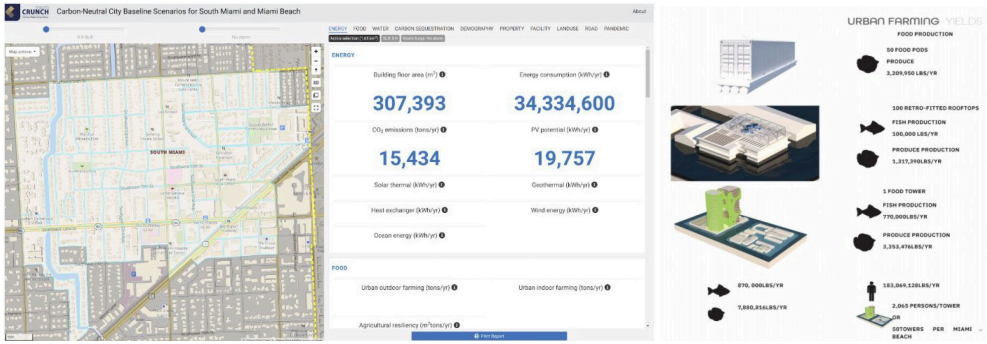


Figure 3
The user interface of the IDDS beta application showing an interactive selection (highlighted on the map) and related statistics on the left and on the right with estimates for urban indoor and outdoor organic food farming resource usage and site-specific building designs above the sea level rise and new preventive storm surge height zone for the period from 2060 to 2100 by D10 student Jorge Vasquez Valdiviezo, Phillip Pretell, and Rendy Vincent . (FIU-CRUNCH-GIS, Dr Juhasz Levente SS 2019 to SP 2020).

## 1.F. IDSS API AND DATABASE

To present these statistics in a web environment, a custom application programming interface (API) was developed for the sole purpose of serving these data over the web. This API connects to a MySQL database that was optimized with multi-column indexes for performance. The API accepts HTTP GET requests through six endpoints that correspond to five socio-economic categories and food-energy-water nexus parameters. The web application makes calls to this API depending on the census block selection. That is, upon request, for any given combination of blocks within the boundaries of study cities, the API returns estimations for energy consumption, water consumption, etc. for those specified areas. For the socio-economic variables, two additional parameters corresponding to SLR and storm values can also be supplied in order to get results for different combinations of SLR and storm scenarios.

## 1.G. IDSS VECTOR TILES

Serving geographic data can be slow with traditional GIS methods due to the size and complexity of datasets. For this reason, this application utilizes a modern concept and serves geospatial data in the form of vector tiles. The tile system divides the Earth into spatially nested tiles with gradually smaller size and more details and only transfers a subset of the original dataset. For a description, see e.g. Juhász and Hochmair (2016). Vector tiles transfer geospatial data with vector geometries, which can be exploited for fast and dynamic in-browser visualization. The application uses two types of tiles: inundation tiles generated from binary inundation layers and background map tiles based on OpenStreetMap (OSM) data. Inundation tiles are built with polygon geometries through the processing framework. Each polygon contains two values, which are the minimum SLR and the storm scenario in which they become inundated. The visual appearance of features stored as vector styles can be modified on the fly in a web map. As a result, inundation scenarios can be quickly changed by filtering these attributes. The same flexibility applies for the background map.

## 1.H. IDSS USER INTERFACE

The user interface was written in JavaScript and is running as in a Node.js container. The design of the user interface was aimed at providing an easy to use interface for users to instantly see the social and economic impact of SLR and storm surge inundation and properties related to the water, food and energy nexus within the study cities. The interface is divided into a map viewer and a statistics report area. The map viewer provides spatial interactivity, such as selecting custom areas within cities, interactive zooming, etc. The other main component of the user interface is the statistics reporting tool which is achieved by dynamically created and updated charts.

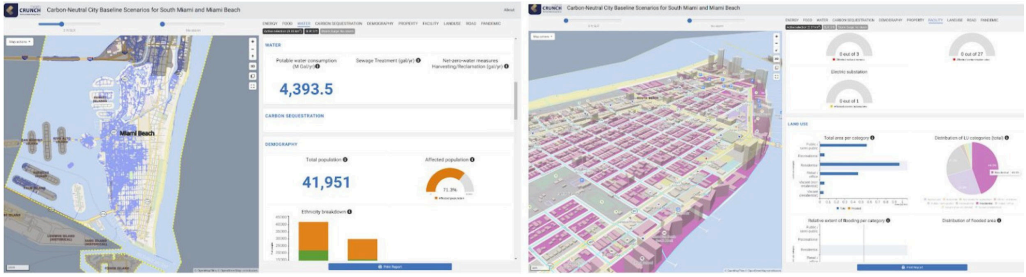


Figure 4
Left image: The user interfaces visualizing 3ft of SLR and reporting potential impacted resident demographics. Right Image: 3D mode showing Miami Beach. (CRUNCH-GIS, Juhasz Levente SS 2019 to SP2020).

## 1.I. IDSS APPLICATION FUNCTIONALITY

The main functionality of the application is to present and visualize details for a user selected area within the study cities. Figure 4. highlights such a selection on the map interface, while not selected areas are greyed out. Users are able to interactively change the selection. Upon selecting an area, the statistics on the right pane are dynamically updated. The beta version of the application shown in Figure 4. currently displays estimated floor area, energy consumption, CO2 and PV potential for the selected area. Users also have the option to select entire cities at once.

Another main function of the application is the dynamic visualization of SLR and storm surge inundations. This is done by adjusting the sliders on top of the map panel. Figure 5. shows a scenario 3 ft of SLR in Miami Beach. Socio-economic variables corresponding to this level of inundation inside the user-selected area are reflected in charts on the right side (i.e. Demography, Property, Facility, Land Use and Road). Information corresponding to these categories reflect the current settings (SLR and storm surge) inside the selected area and all statistics groups present information for both totals and affected counts or values (i.e. population, property value). Changes in inundation level settings and area selection are instantly reflected in both the map and statistics panes. This dynamic relationship empowers users to interactively explore and study the potential impact of climate change and to also get information about the energy-food-water nexus. On the application level, each change triggers five API calls to load statistics for each topic category. To improve performance, data caching is also implemented so that previously loaded scenarios can be displayed without loading data through the API again. Several other features have also been implemented to aid the interpretation of results. For example, the size of the selected area is dynamically calculated and reported in the interface. Additional GIS layers, such as land use (Figure 4) can also be turned on to be rendered on the map. Furthermore, these polygons are dynamically linked with the corresponding statistics.

## PART 2: CARBON-NEUTRAL AND SYNTHETIC BIOLOGY-INSPIRED DESIGN STUDIO EXPERIMENTS RANGING FROM 2018 TO 2100

The CRUNCH research studios have been working on a series of resilient design projects for the City of Miami Beach and South Miami since Fall 2018. Only a small fraction of the entire experimental results can be discussed in this research paper. One specific scenario presents a stage of the flooded City of Miami Beach for the year 2100. All new buildings are 25-30 feet above the current sea level on stilts, totally off-the-grid and self-sufficient, mixed-use skyscrapers and floating structures. They all have been modeled with Revit-BIM-GBS-Insight360-COVE, Robotic-Structure, Dynamo-Python, Infraworks360, CFD, and generative Fusion360 workflows due to its geometric complexity for carbon-neutral operation, hurricane, and tornado induced resilience im-

pact forces. All the scenarios were modeled during a mixed FIU master research design studio in order to reflect on a type of parametric resilient geometry with real-world engineering applications, technologies and features. This includes multi-functional systems and modules, renewable energies from solar/wind/water/kinetic building skins, autonomous transportation, artificial intelligence (AI), the Internet of Things (IoT), robotics, and urban outdoor and indoor farming with self-healing facade tectonics for climate emergencies in 2100. (Figure 6 and 7).

## 2. A. SYNTHETIC BIOLOGY AND A RENEWABLE ENERGY ABUNDANT SOCIETY

All of these former and current design research projects are in process to be published by FrancoAngeli in Milano (Figure 7) and are also included in the new beta IDDS app organized by topics and indicators based on the Energy-Water-Food Nexus (Figure 7)

Parallel to the project described above we are working with more hypothetical scenarios that look at trends that are outside the main discourse in carbon neutral design. When we architects look at ways to mitigate climate change we tend to go back to just slightly improve the methods and construction techniques with which we created the climate emergency. So what is out there that can radically change our imagination?

In particular, we have begun to follow the trends in the emerging field of Synthetic Biology (SynBio). In the past decade, SynBio has surfaced as the fastest growing technology in human history. SynBio involves emerging techniques that allow us to design, edit, and engineer all kinds of living organisms. Today we can manufacture molecule by molecule: lab-grown meat, bio-grown leather, milk, wood, plants that do not need fertilizer, fuels, fragrances, fabrics, novel pharmaceuticals, and even age-reversal techniques, which has already been proven in mice in laboratories at the Salk Institute in CA. Synthetic Biology was officially born in 2006, but it is growing by a factor of 10 times per year, compared to computer technology that is rising at a factor of 1.5 times per year. But what are the direct surprises SynBio is bringing to us?

## 2.B. BIONET AND THE PB (PERSONAL BIOSYNTHESIZER).

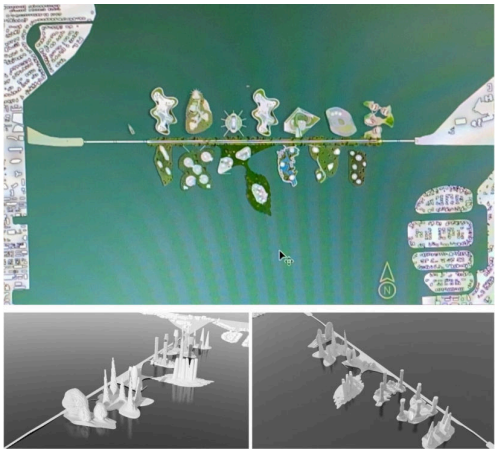

Figure 8
Site plan and axonometric images above and below: The images show the current joint FIU Spring 2020 experimental, carbon-neutral high rise design studio projects of Thomas Spiegelhalter and Alfredo Andia envisioning a series of islands along the I95 freeway of Biscayne Bay between Miami and Miami Beach. Renderings by Alexander Bahensky.

Like the internet, it will allow us to download the DNA code anywhere. Our Personal Bio Synthesizer will let us redesign the DNA and create new organisms and then send them through the BioNet to grow these organisms everywhere where there is distributed DNA manufacturing. Today we are seeing the quick rise of the formate fermentation, not only in the labs but as a disruptive technology in many industries. In the material innovation front we are beginning to see Bio-concrete, Bio-Soils, mushroom-based insulation and lab-grown wood (Figures 8, 9).

## 2.C. TOWARDS AN ABUNDANCE OF BIO-ENERGY CIVILIZATION.

But perhaps one of the most surprising things about the industrialization of SynBio is the emergence of fermentation processes which will allow us quickly to generate high quantities of bioenergy so it will allow us to move from an energy scarcity society to an elec-

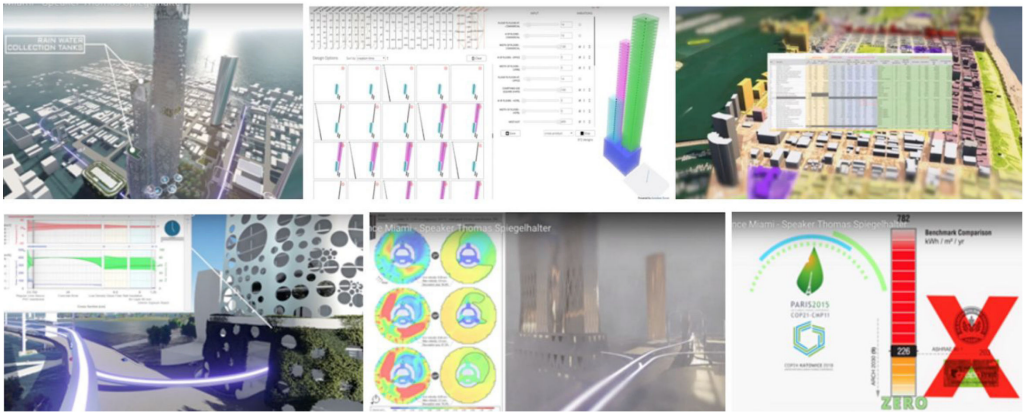


Figure 5
Hypothetical carbon-neutral design scenarios and blue-green infrastructure in 2100 by Sadiel Ojeda, master thesis student 2018. Fitness tests with Computational Fluid Dynamic software for hurricane category 5 forces, WUFI software for temperature, vapour migration and humidity building impact and biomass simulations. Photos and diagrams courtesy of Thomas Spiegelhalter, CRUNCH, 2019.

tricity abundance civilization. Today the total energy supply generated on earth is about 20 TW-year, imagine what will happen to our civilization if we can generate the double of energy, 40 TW-year. We can begin to change for example the total natural fresh water cycle. Architecture buildings design and materials instead of avoiding sunlight can begin to behave more like plants that develop more surfaces to capture the sun.

## 2.D. CARBON-NEUTRAL AND RESILIENT BIO-CITIES

In this more speculative part of the project, we believe that climate change is telling us that we are in a crisis of imagination! To be more precise we began to develop a speculative plan for the Biscayne Bay estuary that envisions infrastructures in Biscayne Bay that grow by themselves using synthetic biology. In this project, we visualize a series of islands and buildings in the estuary of Biscayne Bay which grows by using living matter. Based on previous research on a

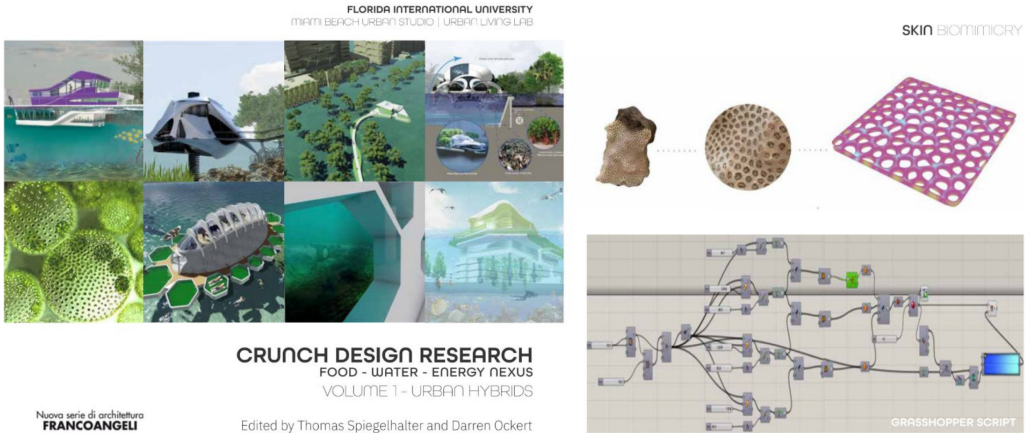


Figure 6
Right and left image: Excerpt of the D8 Studio Design Studio Publication for the F-W-E-Nexus Volume 1 - Urban Hybrids in Miami Beach, FrancoAngeli Milano, 2020, ISBN: 9788891792921 (CRUNCH PI Thomas Spiegelhalter and Darren Ockert, F 2018).

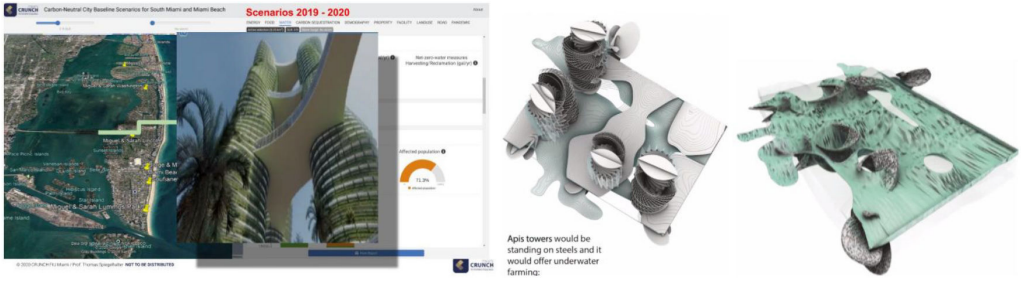


Figure 7
D9 SP 2020 Design Studio scenario 2020-2100 for the IDSS app by Alexander Bahensky and Patrik Osvaldo (left image) and Laura Gomez and Sophia Neves (right image) of Studio Spiegelhalter. Publication of Volume 2 - Miami Bay Hybrids, FrancoAngeli Milano, 2020. (CRUNCH PI Thomas Spiegelhalter and Alfredo Andia D9 Studios, SP 2020).

gene circuitry that uses bacteria that has the ability to precipitate calcite to solidify sand we envision the growth of a series of islands over the shallow Biscayne Bay as a way to create a "living shoreline" for relocating populations from Miami threatened by sea-level rise. These growing territories will have increased soil pressure that will self-transform according to the levels of rising seas. The proposed system of islands works like atolls that will create defences from currents and surges.

The infrastructures above the islands are designed for living, entertainment, work, food production and functions such as water desalination. Synthetic Biology has the possibility to make living matter fully programmable. In this project, we try to challenge our imagination and move more deeply into bio-aesthetics. We find the process very difficult to visualize with traditional architectural methods and thinking. One of the main drivers is to observe biological agents that could activate spatial evolution and how our bodies will be augmented in a SynBio age. Each project we work on is developed based on particularly desirable conditions, we study particular processes of growth, and investigate what makes an organism develop their shape.

## 2.E. TECHNOLOGY VS. FICTION

Fiction can be a taboo in architecture. The method of making SynBio inhabits as a different epistemic space than traditional scientific discovery, by celebrating making synthetic biology has a deeper relationship with envisioning. In this project, at first, we tried to find existing SynBio techniques. We studied processes that could produce quick methods and low energy practices of biomineralization such as sporosarcina pasteurii bacteria, synthetic protein, and collagen to produce artificial bone materials, synthetic spider silk, and others. However, after conversations with several SynBio researchers, we were convinced that the next plateau of SynBio was envisioning fiction, not just technology. A space in which the next generation of SynBio can begin to reinvent itself.

## CONCLUSION AND FUTURE WORK

Designers are often unable to adequately explore alternatives of their impact on the environment, on energy, water, and resource consumption with GHG's benchmarks upfront. This leads to an alarming literacy, which represents the dilemma of the AEC industry and the design culture with the well-published climate emergencies worldwide. Any integrated project delivery process must require early on participatory cloud-based master planning with machine learning and deep neural learning processes to retrieve feedback for all project domains, for coding, interoperability among different expert domains and plug-in platforms for shared modelling, analysis, and fitness test processes.

Our critically discussed analysis, and automated cloud-based optimization workflows, with experimental design research testing, are not finalized and more work needs to be done. We need to keep asking and testing what will be a carbon-neutral AI-

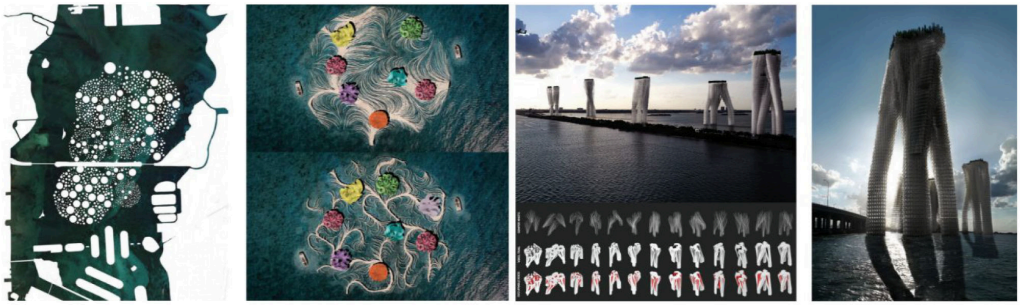

Figure 9
This speculative project envisions a series of islands that grow in Biscayne Bay by reengineering cyanobacteria. A biological circuitry allows cyanobacteria to capture carbon dioxide in the water via photosynthesis and transforms it into finely layered rock material. The process is similar to the living stromatolites that were abundant in the Precambrian age. Cyanobacteria created the earth's atmosphere. Left image: Site plan, 2018. Right image: a project by Daniela Romero & Solange Salinas (A, Andia D8 Studio, FIU, F 2019). Desalinization, absorption, and retention tower that follows the process of growth via aggregation through a semper's knot weight distribution; a project by Renzo Lopez (A, Andia D8 Studio, FIU, SP 2018)

powered smart, green-blue and resilient infrastructure for coastal cities in 10, 30, or 80 years from now on look like? There is no ending and much exploration and testing needed in the future to identify feasible solutions as the compound effects are extremely complex to model and is still an open research question, therefore our approach uses mostly simplistic scenarios of testing all workflows together.

## ACKNOWLEDGMENTS

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# Self-shaping Textiles

## *A material platform for digitally designed, material-informed surface elements*

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*Despite the cutting edge developments in science and technology, architecture to a large extent still tends to favor form over matter by forcing materials into predefined, often superficial geometries, with functional aspects relegated to materials or energy demanding mechanized systems. Biomaterials research has instead shown a variety of physical architectures in which form and matter are intimately related (Fratzl, Weinkamer, 2007). We take inspiration from the morphogenetic processes taking place in plants' leaves (Sharon et al., 2007), where intricate three-dimensional surfaces originate from in-plane growth distributions, and propose the use of 3D printing on pre-stretched textiles (Tibbits, 2017) as an alternative, material-based, form-finding technique. We 3D print open fiber bundles, analyze the resulting wrinkling phenomenon and use it as a design strategy for creating three-dimensional textile surfaces. As additive manufacturing becomes more and more affordable, materials more intelligent and robust, the proposed form-finding technique has a lot of potential for designing efficient textile structures with optimized structural performance and minimal usage of material.*

**Keywords:** *self-shaping textiles, material form-finding, wrinkling, surface instabilities, bio-inspired design, leaf morphogenesis*

### INTRODUCTION & STATE OF THE ART

The Industrial Revolution has mostly shaped the world we live in. Over the years it led to the over-exploitation of natural resources, ever-increasing environmental footprint and waste generation. Although science and technology have greatly advanced, the way we build did not evolve much. Other disciplines adapt new technologies much faster than architecture - as it is immensely complex, deeply rooted in the tradition, resistant towards changes and dictated by the needs of the market. However the rapid technological developments and material innovations in other fields increasingly challenge the refractory architectural conventions. Recent technological advancements and developments on the level of material composition increasingly affect the

design practices. Combination of the new fabrication methods and advanced material research leads to the expansion of a new domain exploring robust and intrinsically efficient design solutions where the material is favoured over the form. One of the earliest contributions to this flourishing field was provided by the MIT Self-Assembly Lab directed by Skylar Tibbits, exploring various manifestations of active matter - *"a newly emerging field focused on physical materials that can assemble themselves, transform autonomously, and sense, react, or compute based on internal and external information."* (Tibbits, 2017)

As part of this material investigation, the Self-assembly lab developed a method for transforming textiles into desired three-dimensional shapes. This methodology relies on 3D printing a more rigid material such as thermoplastics on top of an elastic, pre-stressed fabric. After the tension is released from the fabric, the textile transforms into a three-dimensional shape as means to find a balanced state. The first case-study developed with this technique was the "Active shoe", where material of varied height and property was printed onto pre-stretched fabric [1].

This methodology was further elaborated by the group of Schmelzeisen et al. at the Institut für Textiltechnik (ITA) of RTWH Aachen University, who formulated the concept of 4D Textiles as the combination of textiles, 3D printing and a time dependent element. (Schmelzeisen et al., 2018). According to their definition, 4D textiles utilize pre-stretched fabric as energy storage. Once the stored energy is released, it leads to the structural change of the system and its spatial transformation. Schmelzeisen argues that such systems could have multiple stable structural forms which could be switched back and forth by applying additional energy such as for example heat.

As additive manufacturing becomes increasingly accessible and affordable, more and more people experiment with 3D printing on pre-stretched textiles. One of the commonly studied aspects became the reverse engineering of a target three-dimensional form, also called the inverse problem.

Design studio Nervous Systems used Boundary-First Flattening algorithm and OpenFrameworks software to compute a 2D pattern of stiff hexagonal tesserae 3D-printed on the stretched fabric which would morph into a desired three-dimensional shape.[2] The algorithm computes the Gaussian curvature of the target surface, then computes the local change in metric needed to flatten it. The obtained map informs the size of the hexagonal tiles to be printed on the fabric: map areas that got stretched/-contracted upon flattening will be printed with smaller/larger hexagons. Upon release of the fabric tension, the fabric will contract more/less in the areas covered with smaller/larger hexagons, hence locally retrieving the Gaussian curvature and morphing into the target shape. Since the tiles are quite thick (they have high thickness to radius ratio) they will not deform in response to the fabric tension release, instead the fabric deforms only in the interstitial space between the tesserae. Therefore this approach uses the 3D printed tiles essentially as rigid elements that locally constrain the fabric to its stretched state.

A different approach to the design of target surfaces is pursued by Perez and coauthors (Perez et al., 2017) from URJC Madrid and Disney Research, who developed computational tools for simulating the morphing of networks of thin elastic rods 3D printed on pre-stretched membranes. Their approach is complementary to the one developed by Nervous Systems in which 3D printed tiles are surrounded by stretchable fabric because here the fabric is subdivided into patches surrounded by 3D printed material. This allows them to model the 3D printed textiles as Kirchhoff-Plateau surfaces, which involve some peculiarities. First, the release of stress in a pre-stretched fabric attached to a (more) rigid boundary approximates the minimal surface problem (Otto, 1973) and therefore would give rise to surfaces with vanishing mean curvature. Second, the finite rigidity of the 3D printed rods will cause them to deform into shapes that must satisfy an equilibrium state of the rods, which (because of the compression exerted by the fabric) could result in highly wrinkled configura-

tions, therefore leading to possible multiple equilibrium states that are difficult to choose from. Consequently, the authors provide a semi-automated digital tool to design a 3D printed pre-stretched fabric that satisfies a global target surface, but explicitly avoids sagging and wrinkling of the membrane by requiring a sufficient amount of membrane stretch and a high enough rigidity of the rods (obtained by increasing the rods thickness and width).

Other examples look at analogue processes by applying slightly different digital fabrication techniques, such as tailored fiber placement rather than 3D printing (Aldinger et al., 2018). The majority of case studies exploring self-shaping textiles focus on the process of simulating or fabricating target three-dimensional geometries. This approach resembles a common trend in the architectural practice where the form comes first and materials need to follow.

Against this tendency, the last decade has seen a strong interest towards Nature-inspired design strategies, such as the theory of Material Ecology (Oxman, 2010). Although we are now much more capable of imitating Nature's design strategies by using digital manufacturing techniques to "grow" materials into shapes, these tools still exacerbate the predominance of form over matter, of information over its physical substrate.

Complementary, in the last years a number of morphogenetic studies have shown how leaves, flowers (or their artificial counterparts) acquire their shape through spatial and temporal patterns of growth, together with varying mechanical properties of the underlying tissues, rather than a strict genetic control of the morphogenetic process itself (Prusinkiewicz et al., 2010; Liang et al., 2009; Sidney Gladman et al., 2016). Therefore these studies investigate the so-called forward problem, that is, given a certain distribution of growth in a thin body, understand which final shapes can be acquired. Moreover, since these morphogenetic processes are essentially scale-free, these findings are extremely relevant for the exploration of alternative routes towards shape generation for design and architectural applications as well.

## RESEARCH GOALS

Contrary to the other top-down approaches aiming to develop material processes which form target geometries, our bottom-up methodology relies on the experimental exploration of this technique -that is 3D printing on pre-stretched textiles- and aims at learning how the materiality of our specific system can lead to unexpected morphing behavior. For our experiments we chose a thick elastic fabric on top of which we deposit thin layers of PLA thermoplastics.

Figure 1
Lines with varying thickness (0.3 mm, 0.6 mm, 1.2 mm) printed on a 150% pre-stretched fabric.(left) Lines with 0.3 mm thickness printed on differently pre-stretched fabric (130%, 150%, 176%) (right)

Due to our choice of thick textile and thin plastics, we "discovered" wrinkling as an unexpected result. The wrinkling phenomenon was not discussed in this context before and therefore becomes a complimentary contribution to the field/state of the art. As it will become clear in the remainder of this article, the novelty of our work resides in the following elements: forward problem instead of inverse problem, wrinkling and fiber bundles. Our aim is **to use wrinkling in pre-stretched textiles as a design tool** for the generation of forms and surfaces. We validate our approach by replicating morphogenetic processes leading to the leaf-like shapes that are known from the scientific literature in biology, physics, and mechanics.

## EXPERIMENTAL RESULTS

We start our series of experiments from the characterization of single lines. We 3D print straight lines of various thickness on differently stretched fabric. After releasing the tension, we analyze the morphology of the models and their geometrical characteristics. The experiments show that both parameters- the prestretch of the fabric and thickness of the deposited lines- significantly alter the wrinkling behaviour. We observe that for a given choice of line thickness the total number of waves per total length of the printed line is a constant number, independent of the prestretch (Figure 1 left): this means that the wrinkles' wavelength at the onset of wrinkling is only dependent on the line thickness (Figure 2). Instead, increasing/decreasing the prestretch for a given line thickness will result in narrower/broader wavelengths and higher/lower amplitudes, similar to how an accordion deforms (Figure 1 right).

In the second series of experiments we study curved lines deposited on both uniaxially and biaxially stretched fabric (Figure 3). In the case of equibiaxial stretching we observe that the line orientation does not affect the wrinkling, that is, the wrinkles are evenly spaced on each line and their wavelength is the same as for the straight line case. For a uniaxially stretched fabric instead the wrinkles are dependent on the prestretch direction: they are most evident along the prestretch direction, and they flatten more and more as the printed lines approach the perpendicular direction.

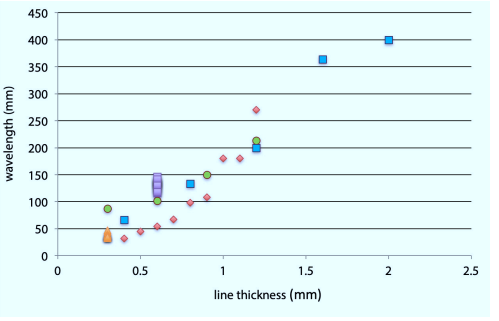


Figure 2
Plot representing the relationship between wavelength of the wrinkles at their onset and line thickness. Each marker indicates a different printing batch.

The following set of experiments examines the behaviour of multiple parallel lines (Figure 4). Since the straight lines preserve translational symmetry but are separated by a fixed finite spacing, this study serves to transition from a 1D system towards a 2D system. Contrary to the examples mentioned in the state of the art, we look here at **fibers bundles rather than fibers networks**, that is we never have patches of textiles enclosed by a continuous stiff edge clearly distancing our work from that of Perez and colleagues introduced earlier.

Here we present our results as a phase diagram of all the shapes that we obtained by independently varying the interline spacing (s) and the line thickness (t), obtaining a 8 by 3 matrix (s=0, 5, 10, 15, 20, 25, 30, 35; t=0.3, 0.6, 0.9). Based on our observations, we classify all **morphed shapes** into four distinct types: **bending, rolling, coherent wrinkles, independent wrinkles**, which result depending on the line thickness and spacing (Figure 4-8). Although empirical, this classification proves suitable to qualitatively understand the morphing process. In general, increasing the line thickness (going "upwards" in the phase diagram in Figure 5) results in wrinkles getting larger and wider, until the fabric transitions from a wrinkled to a rolled shape (a roll starts appearing when the

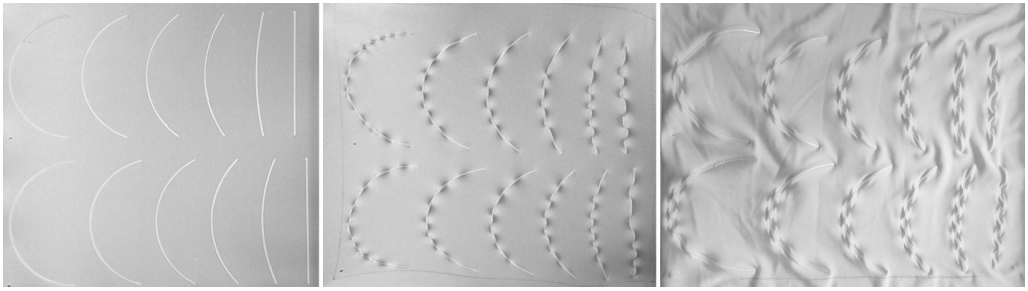

Figure 3
3D printed arcs: before tension release (left), after tension release from an equibiaxial stretch (center), after tension release from a uniaxial stretch aligned with the vertical (right).

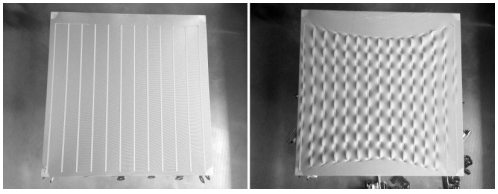

Figure 4
Wrinkles formation. Multiple parallel lines printed on pre-stretched fabric: before tension release (left) and after partial tension release (right) where they wrinkle coherently.

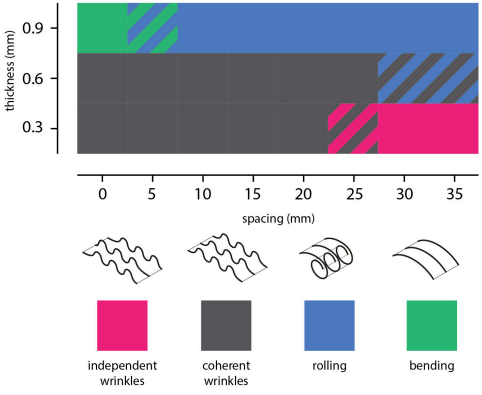


Figure 5
Phase diagram explaining the influence of line thickness and spacing between multiple parallel lines onto the morphed shape. These shapes are classified into four categories: bending, rolling, coherent wrinkles and independent wrinkles

wrinkle wavelength is comparable with the length of the line itself).

This behavior is modulated by the lines spacing: the smaller the spacing, the more the lines will resist the fabric contraction, the less the fabric will bend (Figure 5, at t=0.9 going from s=10 to s=0 the morphed shape transitions from ”rolling” to ”bending”). Conversely, at very large spacing, neighboring lines do not ”feel” each other, therefore they behave as if they were isolated, wrinkling according to what shown in Figure 1 and 2. As the spacing gets smaller, the tension in the fabric between two lines doesn't vanish which causes the lines to wrinkle coherently (that is the wrinkles are aligned and in phase). This behavior is modulated by the effect of the line thickness: for the same spacing, thicker lines exert more tension on the fabric and therefore they cause the wrinkles to align (Figure 5, compare for example going from t=0.3 to t=0.6 at s=25). Therefore we conclude that the line spacing is an important factor affecting the morphing of the fabric, moreover interacting in a non-trivial way with the effect of line thickness. All of the aforementioned morphed shapes and their dependence from the lines' thickness and spacing are qualitatively captured by preliminary finite element simulations which we will develop further in future research (Figure 6).

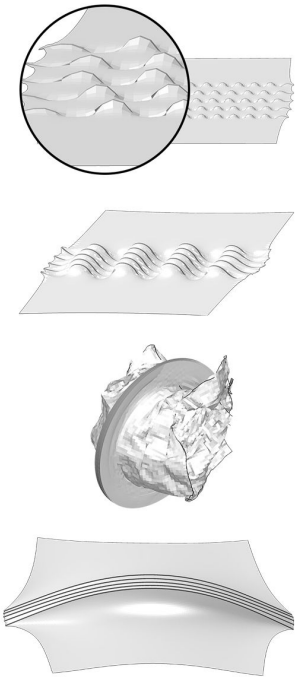

Figure 6
Postbuckling configurations of multiple parallel lines with varying thickness (t - mm) and spacing (s - mm) obtained through finite element simulations. These morphed shapes closely match those observed in the experiments, and qualitatively follow the phase diagram of Figure 5. From top to bottom: independent wrinkles (t=0.08, s=45); coherent wrinkles (t=0.2; s=27.5); rolling (t=0.5; s=42.5); bending (t=1; s=10).

To validate our morphing strategy based on fiber bundles we seek to replicate target leaf-like shapes studied in the scientific literature, such as the kale and salad leaf shapes (Figure 9). These leaves are characterized by moderately curved leaves with highly rippled edges. During their morphogenesis the leaves grow more at the edge than at their base, causing this peculiar shape. More precisely, a highly concentrated growth at the leaf edge, causes edge ripples with a flat center, whereas a more uniformly distributed one results in a saddle shape over the entire leaf. In particular a growth profile varying exponentially from edge to base produces fractal wrinkles with an increasing wrinkling frequency from center to edge. (Sharon et al., 2007; Liang et al., 2009; Prusinkiewicz et al. 2010). Comparing our 3D printed textiles material system with the salad leaf example, we note two fundamental differences : 1) leaves are made of a single material whereas our 3D printed textiles are composed of two materials; 2) the morphogenetic process in leaves happens due to a spatially inhomogeneous expansion, whereas our textiles morph upon contraction due to confinement release. This means that whereas the undulations appearing in leaves are a way to release compression stress on the faster growing edges, in our case the textile will at most be under tension stress close to the 3D printed fibers, which are under compression.

Therefore, to replicate the salad leaf shape, our strategy is to place 3D printed lines on the textile such that the wrinkling is more pronounced at the edge than the base. To this end (Figure 10), we print the edge as a large 90° circular arc (of radius $r_0$=360 mm and thickness $t_0$=0.3) and two more concentric arcs of increasing thickness (respectively with dimensions: $r_1$=280 mm, $t_1$=0.6 mm; $r_2$= 200 mm, $t_2$=0.9 mm). The thicknesses of the lines were chosen according to Figure 2 to obtain a marked decrease of the wrinkles frequency from edge to center (Figure 10, center). The radial distance between arcs was chosen large enough to avoid tension in the fabric and hence ensuring that the lines would wrinkle independently. To ensure a constant wrinkling frequency along each line we choose a uniform biaxial stretching thus avoiding orientation dependence of wrinkling on the arcs lines as seen in Figure 3.

Finally we note that we avoid fully enclosing a circular patch of fabric (which would result in a minimal surface approaching the "potato-chip" shape due to uniform residual tension in the fabric whereas we chose to print fibers on a quarter of circle so that the tension on the fabric away from the lines vanishes. The resulting shape is quite similar to a typical salad/kale leaf, with larger portions of slightly curved fabric at the base/center, and coarse wrinkles branching into increasingly tighter one towards the edge.

Figure 7
Single lines printed with decreasing line thickness showing the transition from bending to rolling to wrinkling behavior (from left to right).

Figure 8
Multiple parallel lines printed with decreasing spacing (15, 10, 5, 0 mm) showing the influence of the spacing on the morphing behavior (from tight rolling towards bending).

Figure 9
Salad leaf, with high frequency wrinkles at the edges, and moderately curved geometry closer to the leaf base.

## DISCUSSION AND CONCLUSIONS

Our methodology differs significantly from other studies of 3D printing on pre-stressed textiles. Rather than fabricating predefined geometries and reverse engineering given forms, we aim to leverage the self-shaping properties of the material as a way to discover new forms and topologies. We use the wrinkling phenomenon as a design driver for the development of three-dimensional geometries that are intrinsically efficient because they mediate between the tension and compression of the two materials they are composed of. Nevertheless, our methodol-

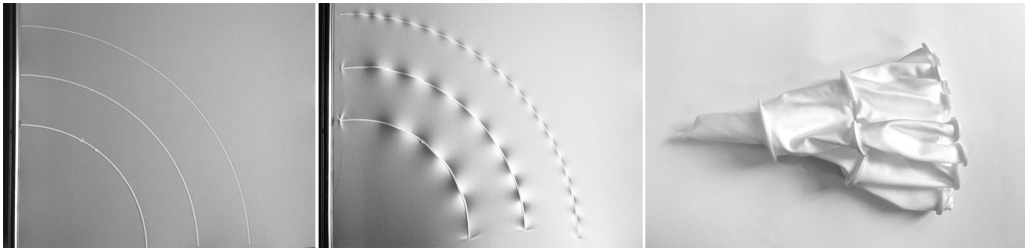

Figure 10
Model of a salad leaf, obtained by printing three concentric arcs with increasing thickness from periphery to center (r0=360 mm, t0=0.3; r1=280 mm, t1=0.6 mm; r2= 200 mm, t2=0.9 mm). Equibiaxially pre-stretched state (left). Partial tension release (center). Full tension release and detached from the printing bed.

ogy is not free of limitations. It does not provide a solution for producing any desired form and favors certain geometries such as curved over flat lines and surfaces.

In the next phase of the research we are planning to extend the shape analysis of the wrinkled textiles through 3D scanning (Figure 11, left). In this way we could refine our analysis (which currently is limited only to the wavelength at onset of buckling) to quantitatively describe the geometry of the textile in the far post-buckling regime, hence quantifying shape descriptors such as: lines waveform and frequency; mean and Gaussian curvature of the fabric; etc. Moreover, we will systematically explore the morphing behavior of self-shaping textiles based on fiber bundles through a parametric finite element model (Figure 11, right) in which the geometrical parameters that we accounted for (line thickness, interline spacing) can be densely sampled at a reasonable computational cost and without the inaccuracies intrinsic to the experiments. Comparing the shape descriptors from the 3D scans with those derived from the finite element analysis, we will be able to propose an analytical model of wrinkling in self-shaping textiles based on fiber bundles. To this end we will resolve to rod and membrane theory to better interpret our empirical and simulation results thus obtaining quantitative predictions of the morphing process.

Another aspect to be looked at is differentiating the deposited materials as a way to increase the spectrum of design possibilities and allowing to preprogram the textiles not only by defining their geometrical properties but also the material characteristics. Multi-material 3D printing would allow to create heterogeneous textile composites with different local properties. Moreover, external factors such as heat could be further explored in order to change the material properties of the 3D printed thermolastic (Schmelzeisen et al., 2018). Once the filament exceeds its glass transition temperature, it becomes more soft and malleable, thus enabling a second morphing. As a result, it could contribute to the development of adaptable or responsive surfaces with plenty of potential applications in the architectural domain.

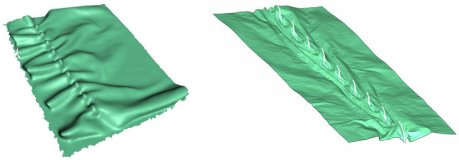

Figure 11
Left: 3D scan of a single line 3D printed on pre-stretched fabric. Right: Finite element simulation of a single line 3D printed on pre-stretched fabric

Our focus on fiber bundles rather than fiber networks has implications not only on the range of possible geometrical solutions, but also on the production process of possible surfaces. Textile industry converts continuous yarns into fibers, and fibers into continuous fabrics. 3D printing of continuous lines (rather than closed patches) allows for imagining the out-of-the roll 3D printing on infinite textiles. Once the 3D printing method is also upscaled into a continuous fabrication process (Rivera et al., 2017), it could become a resource of potentially new architectural applications such as exterior facade systems, roof canopies, temporary structures or interior surface el-

ements improving inner lighting conditions, acoustics, humidity or ventilation.

As facades negotiate between the idealized indoor conditions and ever-changing climate, its design can help to minimize the energy used for heating, cooling, lighting and ventilating spaces. Controlled wrinkling allows to increase surface area, introduce self-shading, and -by changing the surface texture- influence the hygroscopic properties and evaporative cooling and as such, design of wrinkled surfaces could become an efficient strategy for passive cooling or shading of second building skins. More specifically, wrinkled surface elements with targeted shape could be integrated in a building skin to modify the flow of air at the boundary layer thus affecting convective thermal exchange and evaporative cooling of building envelopes and as a result improving microclimate and thermal comfort. Moreover, the wrinkling pattern and amplitude could be adjusted to the local climate requirements and latitude. (Figure 12)

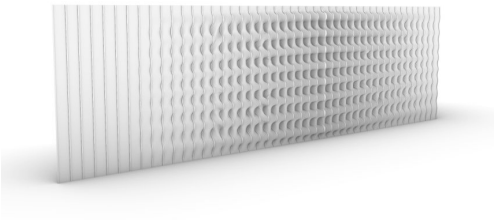

Figure 12
Visualization of a 3D surface gradually transitioning from flat to wrinkled.

Textiles have played an important role in the development of the architecture and building construction sector since millenia, but the majority of architectural textiles are framed and bereft of their intrinsic material properties such as flexibility, softness and adaptability. Our methodology allows us to envision novel textile tectonics of continuous, soft and adaptable spaces.

## MATERIALS AND METHODS

**3D printing on prestretched textile** - For all our experiments we used a thick elastic fabric: Bi Stretch 80% Polyamide (PA) 20% Elastane (EA) CA.280 g/m (150 cm wide roll) from Fucotex on top of which we deposited thin layers of polylactic acid (from spools of 1.75 mm thick thermoplastic PLA filament). All prints have been performed on a custom built Fused Deposition Modelling printer, equipped with Volcano hotend, using a 1 mm nozzle at a temperature of 230 °C and a BuildTak printing foil glued on top of an aluminium not heated, 50x50 cm printing bed. Prior to each print the fabric was stretched to the desired amount and clamped on the printing bed with 50 mm long paper clips. To achieve an equibiaxial stretch of 50% we draw a 33.33x33.33 cm square on the fabric using a cardboard cut-out, then stretch the fabric until the square matches the printing bed outer contour, then clamp the fabric with the paper clips.

**Finite Element analysis** - We used finite element analysis (Abaqus 6.19, Dassault Systémes ) to simulate the morphing of 3D printed textiles with geometries analogous to our experiments. For all our models, the 50x50 cm fabric and 50 cm long rectangular rods were respectively discretized into linear membrane elements and linear shell elements (average size 5 mm); the fabric thickness was set at 0.2 mm, whereas the rods' thickness and interline spacing is given in the captions text. Both the fabric and rods' materials were modeled as isotropic elastic with Young's moduli $E_{fabric} = 50Pa, E_{rods} = 3.5MPa$ and Poisson's ratios $\nu_{fabric} = 0.4, \nu_{rods} = 0.3$. Both materials were assigned an unphysical density value of 1E-3 g/cm$^3$ (see below). To trigger the textile's morphing a uniform prestress was applied on the fabric boundaries. The prestress value (3.379 E-05 MPa) was chosen as the one that would restore the 33.33x33.33 cm reference size in a fabric-only model. The morphed configurations were calculated by ramping the prestress to zero in quasi-static conditions using a Dynamic, Implicit step, with a non-linear geometry assump-

tion. The unphysically low value of material density chosen allowed us to balance out two contrasting needs: eliminating unphysical inertia effects while maximizing the stable time increment.

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# An open-source bio-based material system development for sustainable digital fabrication

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*The development of bio-based material systems and their correlation with digital design and fabrication processes is an ever-evolving area of research with a number of experimental investigations. One such direction of investigation is related to the use of mycelium-based materials, which can minimize environmental impact and energy consumption during production, but also can allow alternative sustainable construction approaches to come to the fore. This work proposes an open-source mycelium-based construction material development, emphasizing on three interrelated steps. Firstly, the fungi growth based on Pleurotus ostreatus mycelium. Secondly, the digital production of custom formworks and material casting for uniform growth and building components creation. Finally, the construction technique investigation based on layering and stabilization of components. Through the suggested open-source bio-based material system development, the aim is to provide an alternative approach in construction that involves an ecological material with low environmental impact, interrelated with digital fabrication and assembly processes. This might open new directions of investigation to the wider architecture and construction community, allowing further consideration and possible implementation of mycelium material towards a more sustainable construction.*

**Keywords:** *Bio-based material, mycelium growth, digital fabrication, construction systems, sustainable construction*

## INTRODUCTION

The contemporary architectural practice and research that is based on digital design and fabrication processes, often follows examples from nature and its material properties in order to use them as potential design drivers of form-generation. Design from nature is not something new, since its value to a sustainable architecture has been recognized, extensively discussed and analyzed (Benyus 2009; Steadman 2018). This direction of exploration is being triggered by bio-inspired technologies, giving rise to notions such as biomimetics or biomimicry (Vin-

cent 2014; Benyus 2009), where examples from nature are used in design due to their ability to achieve shape and structure formation through local optima processes, as material organization and composition are informed by structural and environmental stimuli (Brady 1985). Thus, material resources during production can be efficiently used, through material-specific design concepts and constructive durability, thanks to the seamless integration of design and fabrication (Oxman 2012). Hence, nowadays several projects based on digital technologies attempt to integrate ecological materials due to their environmental benefits compared to contemporary ones, but also due to their local availability and low cost in combination with high precision and affordability offered by digital technologies without any extra cost (Buswell et al. 2005; De Schutter et al. 2018).

Several examples that implement bio-based materials through digital design and fabrication processes can be found (Araya et al. 2012; Oxman 2012;). Projects using Acetobacter Xylinus, a cellulose product, by (Araya et al. 2012) and Chitin, the second most abundant polymer on the planet, by (Mogas-Soldevila et al. 2014), both use 3D printing technology to create fully recyclable products of temporary architectural components, by controlling their configuration both genetically and physiologically.

Another constantly evolving direction towards bio-based materials and digital technology integration is related to the use of mycelium-based material, due to their superior biodegradability and relative suited mechanical properties (Campbell et al. 2017) but also due to the offered advantages related to local availability, low environmental impact and energy consumption throughout the whole life cycle of the material. In the project of Mycotectural Alpha (Ross 2012) an arch was manually developed using mycelium bricks under compression, demonstrating the structural potential of the specific material and at MYX [1] Oyster mushroom mycelium was cultivated in lamp-form moulds.

In other projects, the application of mycelium-based material was done in parallel with the developed of digital design and fabrication workflows. In the work by [2] a mycelium experimentation was achieved through the application of 3D printing technology. In this case, printed sculptures in small scale were filled with mycelium and agricultural waste for growth into final products, demonstrating materials' cycle in different phases. Other works include among others, the Hy-fi (Nagy et al. 2015) and the Myco Tree projects (Heisel et al. 2017). In the Hy-fi project a large scale installation in the form of a gallery pavilion was developed using mycelium and reflective block as building materials, produced by Ecovatice Design [3] (Holt et al. 2012; Jiang et al. 2016). They were assembled together based on a custom computational stacking logic in order to formulate the overall structure with the addition of supportive wood elements. After several months of staying on-site, the structure was decomposed and the materials were used as a fertilizer (Nagy et al. 2015). In the Myco Tree project a load-bearing spatial branching structure was form-found using 3D graphic static method, enabling a compression-only system to be produced with the use of mycelium and bamboo materials. The moulds were digitally fabricated by Mycotech [4].

Despite the rapid development of architecturally implemented mycelium-based materials, the focus was mostly given to the design or construction of overall morphologies with less concentration or comprehensive discussion on the material production process. This work attempt to fill this gap by presenting an open-source mycelium-based material system development, discussing at the same time digital fabrication and construction techniques involved towards a comprehensive and sustainable design to construction workflow. By focusing on the appropriate embodiment of material in the fabrication process, an alternative approach to construction, where structures with minimum environmental impact, both in terms of energy consumption and waste management, can be achieved.

The study was initiated to research how mycelium structures could serve the needs of an en-

vironmentally conscious approach in protected environments. The general concept of reversibility of design in natural landscapes not only is it desirable, but it is also vital for the endangered species of fauna and flora in these areas. Comprehending the production needs of the material and the life-cycle that follows, future designs can adapt to the process and be optimized. Mycelium-based structures require the fabrication process to be inextricably linked to the material design, thus temporary interventions could serve any functional needs, while promoting the environmental consciousness of the visitors, rather than creating new self-reported attraction points.

More specifically, the selection and production of material is a result of natural process of mycelium growth, where the mushroom's vegetative part is used as a natural glue to transform agricultural waste into an innovative construction material. Primary property of the material is its biodegradability, which occurs after the exposure to high humidity levels, releasing nutrients to soil. Several experiments were conducted to end up with the proposed production of the formwork along with the suitable environmental conditions of the cultivation modular units and systems. According to the material's properties and limitations, a group of differentiated units is designed to serve a custom stacking process. The result is a number of stacking typologies that can be alternated with parameters like porosity, size and function. Following sections describe the three interrelated parts of the research; the fungi growth, the digital fabrication for material growth and the layering and stacking logic of the brick units and systems.

## OVERVIEW OF METHODOLOGY

Architectural design and construction based on nature's principles provide the opportunity for developing effective and optimized solutions that could potentially lead towards an ecological age of architecture, engineering and construction (AEC) industry. In order to achieve results that do not only reduce the environmental impact through minimization of material waste, but also provide additional advantages in terms of built environment and human well-being, comprehensive approaches through the implementation of new materials and techniques are necessary. Regarding the materiality used in today's structures, an important direction is to reconsider the mainstream materials and take into account the massive amount of waste that is being produced. The aim is not only to recycle as much waste as it is feasible after the building is demolished, but also to design with the minimum waste or even with zero-waste. This could be achieved by comprehending the processes that are used in natural structures and mimicking them in architecture, while taking advantage of the advanced computational capabilities that emerging fabrication processes can potentially provide.

Thus, the present research focuses on an alternative way of approaching the design and construction process, where existing natural materials found locally can be analyzed, evaluated and used in design as a starting point for new architectural and construction solutions. The possible steps are summarized below:

1. Material selection and processing through the analysis of available materials, comparison of local natural materials and cultivated, evaluation of environmental impact and cost.
2. Computational design and optimization through the simulation of proposed structures, structural optimization with minimal material and architectural design of functions and spaces to improve human wellbeing.
3. Digital fabrication through emerging technologies implementation and analysis of global warming potential and energy consumption.
4. End of structure's life-cycle, neutral/fertilizing and expected impact on site.

In view of the above steps, material selection is an important aspect of the process that influences the decisions taking place in all other steps of development. In this work, mycelium is selected as the raw material to be investigated. Like any other material, in this case, the specific bio-based material contains

certain requirements and limitations, which are taken into account throughout all steps, which include the production of material, the forming of building units and the assembly logic for construction.

Specifically, steps include the production of material that involves pasteurization of substrate and inoculation. Then, the process continues with custom units forming, which is based on an additive process of material growth in a certain period of time and under specific environmental conditions. In this step, the production of custom modular formworks through digital cutting is important in order for the mixture to be filled and directed to specific custom morphologies while its growth. This is followed by the inactivation of mycelium and its transferred to the site for assembly in the form of custom brick units. Finally, the end of the material's life-cycle and particularly its ability for biodegradation act as a natural fertilized on site in an attempt to offer the material back to nature.

## PRODUCTION OF MYCELIUM-BASED MATERIAL

### *Material selection*

The selected material is an agricultural waste with mycelium acting as the binding material. This is the vegetative part of a fungus or fungus-like bacterial colony, consisting of a mass of branching in the form of thread-like hyphae. Fungal colonies composed of mycelium are found in soil and many other substrates. Mycological fungi considered as an important biomaterial due to its fast growing, non-toxic and sustainable properties, whose use can offer many environmental benefits (Stamets 2005).

Although, its implementation in the field of architecture and construction is still in experimental stage, its advantages have been well recognized. Among others, these include the lack of oil feed-stock usage that makes it beneficial for the environment and leads to a carbon-neutral or a carbon-negative product. Also, its biodegradable nature and its ability to be a fertilizer for the soil makes this material valuable for the conservation of the soil health of protected sites. Finally, it can be characterized as lightweight material with relative high compressive strength that can be produced in considerable low cost (Jones et al. 2020).

### *Production process*

The production process and more specifically the mycelium growth requires specific steps to be followed, with the selection of raw material to be crucial, depending on the purpose applied. The most commonly used types of mycelium used for similar purposes are Pleurotus ostreatus and Ganoderma lucidum. The substrate can be a cereal straw or a mixture of hardwood straw and bran. In case of Pleurotus ostreatus, being a primary decomposer, it grows on a wide variety of wastes high in cellulose. In general, the mycelium is considerably prone to contamination with primary sources the immediate external environment, the culture medium, the culturing equipment, the cultivator and his/her clothes and the mushroom spores or the mycelium. Hence, a number of standards is required in order to effectively perform the production process and to avoid unsuccessful results.

The mycelium growth begins with the agar preparation, which is the medium for fungi growth, usually made in petri dishes. Then, the pure mycelium is isolated for grain media preparation and inoculation. For the incubation of spawn, the pasteurization of the substrate is essential. It can be achieved either with water bath at 70°C for 20-30 minutes or with live steam at 60°C for 6 hours. Then, the inoculum is casted into formworks, where the spawn must be equally distributed so that it will grow uniformly. Then, the mycelium is inactivated, so that it gains strength. During the dehydration process, the blocks should be exposed to 35°C for a few days or to 60°C for one hour (Stamets and Chilton 1983; Stamets 1994).

### *Inactivation process*

Life Cycle Impact Assessment (LCIA) conducted by Ecovative [3] have shown that around 50% of the negative impact of the process comes from the in-

activation of mycelium. Specifically, the analysis was conducted using a conventional oven, heating at 65°C for about one hour. Other methods referred as compatible include microwave and chemical heating. In order to minimize the environmental impact during inactivation, the proposed approach success the method of solar drying. This is an old application of solar energy, that is considered as a rather economical and friendly to the environment procedure for agricultural and food products drying. Figure 1 demonstrates a diagram of the complete production process.

Figure 1
Diagram of the complete production process

### *Biodegradation*

Mycelium itself is a hydrophobic material, meaning that is seemingly repelled from a mass of water. This means that if it was used with no other additional substances it would have a life-cycle of centuries. However, since the substrate is not fully colonized with mycelium and it has direct contact with water, this physical property of the material is invalidated. Thus, when the material absorbs enough amount of humidity, its biodegrading process begins, the bonds holding the substrate together as solid break and eventually the construction is dissolved. Primary experiments conducted within the framework of this work shows biodegradation results of the suggested material (Figure 2).

When the material is exposed to massive amount of water, or in this case is submerged in water, the most rapid absorption occurs within the first three to twelve hours and then the biodegradation process continues in less visible rates for the following days. Although this was an initial experimentation to briefly see the reaction of the sample to the water, mycelium structures are expected to have a different behaviour. Following the suggested structural element dimensions and stacking method analyzed later, the highest percentage of the material is not directly exposed to humidity and rainfall. The first days of the exposure to massive amount of water, the structural reliability of the structures is questioned and should be counter advisable to be visited and in the next weeks or possibly months, depending on the rainfall, the whole structure is expected to be dissolved.

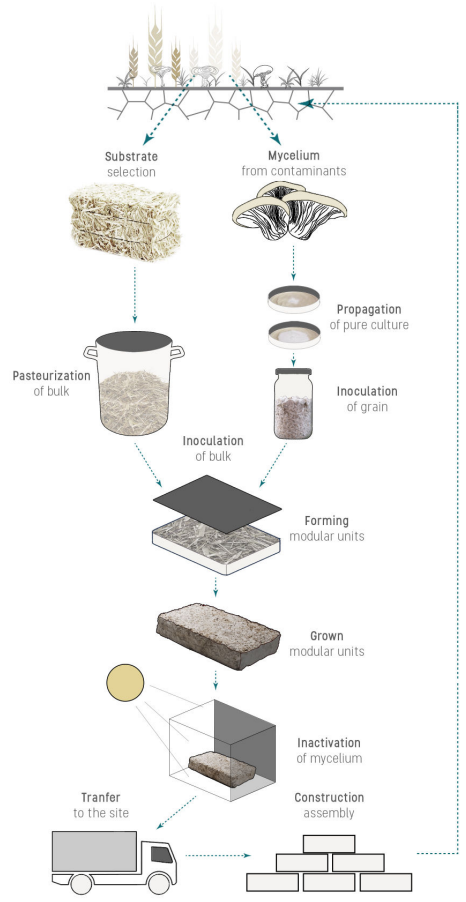


Figure 2
Biodegradation process of the suggested mycelium-based material

Biodegradation is an important property of mycelium-based material and this makes it advan-

tageous over other materials since it allows its complete recycling back to the environment. More specifically, fungi help decompose organic matter and feed on insects and other soil organisms. They also improve soil structure by binding soil particles with mycelium. Some fungi form a symbiotic relationship with plant roots, called mycorrhizae which is vital for many kinds of plants (Jambon et al. 2018).

Although in the specific research the biodegradation is considered as a significant part of the design process, serving the environment after the structure's life-cycle, there have been researches on how to control the absorption properties of the material, by alternating the percentage of the substrates and post-pasteurization processing with hot or cold pressing (Jones et al. 2020). Furthermore, using bio-based coatings, such as polyfurfuryl alcohol resin (PFA), can add water resistance properties (Mokhothu et al. 2017).

### *Experimentation and initial sample prototypes production*

Experimentation and prototypes production was conducted within the framework of this work by setting up a low-tech installation. This allows investigation regarding the most suitable methodology and environmental conditions that can be applied for the production of mycelium-based block prototypes. The mycelium selected for these experiments was Pleurotus ostreatus, since it is a type of mycelium easily cultivated in home or low-tech equipment and facility rooms. The mycelium material was provided by Kyriakides Mushrooms Ltd, in the form of spawn to accelerate the production process and minimize the risk of contamination [5]. The substrate used for the experiments was straw and sawdust in different quantities.

The installation included a clean room in order to reduce contamination risks due to the fact that the air is full of impurities. This low-tech clean box was placed in the interior and was kept in temperatures around 25-30°C and in high humidity. In general, most mushroom clean rooms have a High-efficiency particulate air (HEPA) filter installed to provide clean oxygenated air. Due to the low-tech nature of the suggested set-up an alternative method for minimizing air contaminants was introduced. Figure 3 show the installation of clean box. Figure 4 demonstrates substrate selection and its pasteurization. Figure 5 shows the inoculation of the grain and the growth development in the clean box.

Figure 3
Clean box installation

Figure 4
Substrate selection and pasteurization

Figure 5
Inoculation of grain and growth development

### *Initial sample prototypes*

The inoculation was made when the bulk's temperature was lowered to 26°C. Room temperature was constant at 29°C and substrate temperature was measured to be between 24°C to 27°C. The clean box was high in humidity with no controlled value. The sample prototypes shown in Figure 6 were 9 days grown, while the dehydrated samples were heated in the oven at 65°C for one hour.

The initial samples consisted only of straw and had greater growth rate. Also, the samples with sawdust needed higher percentage of mycelium. Taking into consideration the production processes needed to produce mycelium and compared to straw, that is pasteurized agricultural waste, the target is to use the minimum amount of mycelium that provides the

product with enough compressive strength. The mycelium seemed to develop in an inhomogeneous way, probably because it was not evenly distributed. Further improvements of results could be achieved during experimentation by alternating the environmental conditions. Specifically, the relative humidity of the room should be observed and controlled and the temperature should be as near to 28°C as possible. Moreover, the samples should be exposed to light only when observation is necessary, which was settled during the production of the 1:1 prototypes. Lastly, samples could also be grown with Reishi type of mycelium. Figure 7 demonstrates a series of samples produced during the initial experimentation. Table 1 summarizes samples' ingredients.

Table 1
Material ingredients used for sample prototypes' production

| Sample No | Sawdust | | Straw | | Mycelium | |
|---|---|---|---|---|---|---|
| | % | gr | % | gr | % | gr |
| 1 | 95 | 47.5 | - | - | 5 | 2.5 |
| 2 | 90 | 45 | - | - | 10 | 5 |
| 3 | 85 | 42.5 | - | - | 15 | 7.5 |
| 4 | 80 | 40 | - | - | 20 | 10 |
| 5 | 75 | 37.5 | - | - | 25 | 12.5 |
| 6 | 50 | 25 | - | - | 50 | 25 |
| 7 | - | - | 95 | 47.5 | 5 | 2.5 |
| 8 | - | - | 90 | 45 | 10 | 5 |
| 9 | - | - | 85 | 42.5 | 15 | 7.5 |
| 10 | - | - | 80 | 10 | 20 | 10 |
| 11 | - | - | 75 | 37.5 | 25 | 12.5 |
| 12 | - | - | 50 | 25 | 50 | 25 |
| 13 | 20 | 10 | 60 | 30 | 20 | 10 |
| 14 | 40 | 20 | 40 | 20 | 20 | 10 |
| 15 | 60 | 30 | 20 | 10 | 20 | 10 |
| 16 | - | - | 80 | 40 | 20 | 10 |
| 17 | 30 | 21 | 40 | 28 | 30 | 21 |

Figure 6
Dehydration of an initial sample prototype

Figure 7
Series of sample prototypes produced during experimentation

## MYCELIUM-BASED MODULAR UNITS FORMING

The construction systems suggested in this work consists of modular units made of mycelium-based material outcomes, which are assembled together formulating the overall structures. The production of units is achieved through formworks that required the use of materials with low porosity and the control of the access of air. This can be achieved either using small holes evenly distributed, or with a filtered opening.

In general, the selection of formwork development is based, either on additive or subtractive methods, with the advantages and disadvantages that each process may involve. Since material economy and energy consumption are among the most important factors of choosing mycelium as the material of modular units' construction, formwork development should equally follow these requirements into account. Hence, the level of complexity of the modular units' morphology influences the formwork development, imposing limitations regarding the decisions taken in formwork production stage and vice versa. Formwork development might include recyclability and reusability requirements, with the capability of being readjusted is significant, since it allows effective and minimum energy during the production of mass customized modular units.

For experimental purposes, a series of modular units were developed, aiming to be assemble together creating prototypes of construction systems in scale of 1:1 and 1:2. In this case, formworks were

made by acrylic material that was cut in a CNC laser cutter machine. The design of formwork was influenced by the suggested construction system. In every side surface of the formwork, holes in 2mm diameter were designed and cut so that the mixture was uniformly ventilated (Figure 8).

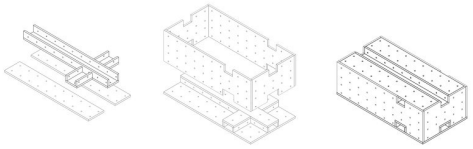


Figure 8
Design and production of a single formwork

For the construction system prototype development, the modular units forming was achieved using Pleurotus ostreatus as the mycelium material with straw as the selected substrate. Two types of formwork (type A and type B) were developed based on the construction technique applied, which were pasteurized and filled with a proportion of 1:4.5, mycelium spawn to straw. The clean room had a constant temperature of 27.8oC and the relative humidity had a range of 45-85%. The developed units, 17 days later, were demoulded and dehydrated in a conventional oven (Figure 9 and Figure 10).

Figure 9
a. Moulded and demoulded unit type A, b. Moulded and demoulded unit type B

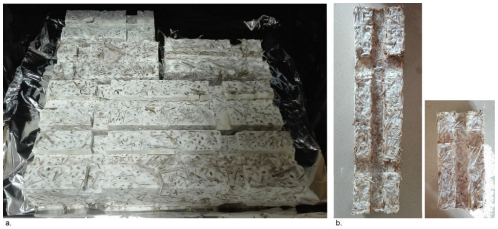


Figure 10
a. Dehydration process of units type A and B, b. Final dried units type A and B

## CONSTRUCTION TECHNIQUE

The construction technique was design-driven by the mycelium-based material properties and limitations but also by the advantages provided by parametric design principles. Through digital development logic the mass customization of a number of typologies and then a large variety of systems were produced based on series of stacking arrangements.

The suggested systems were consisted of a double layer wall for the stabilization of structures due to the highly lightweight nature of material under investigation. More specifically, modular units type A (double length dimensions), were placed perpendicularly, connecting the two layers. Also, additional units were produced to capture corner complexity. Consequently, with respect to standardization, the final row was repeated in the other direction and the long units were passing through the whole length of that side. Afterwards, the long units were split to smaller standard length of type B for their construction (Figure 11).

Different stacking combinations lead to potential arrangements based on modular bricks type A and B. The design of typologies includes notches at three positions (Figure 12), where supporting wooden elements are added in order to enhance stabilization and stiffness of the overall structure (Figure 13).

Different wall arrangements were conducted, demonstrating the flexibility of construction system based on the two proposed typologies (Figure 14). These arrangement results on various case studies with specific openings, both in terms of dimensions and overall percentage. In the design process, the desirable case could be selected for further modification, according to the space's function, orientation and requirements in general.

Figure 15 demonstrates a physical construction system prototype using polystyrene in 1:1 scale and figure 16 shows the respective prototype using the actual mycelium-based material in 1:2 scale based on the suggested stacking logic of modular units' arrangement.

Figure 11
Suggested construction concept based on modular brick stacking

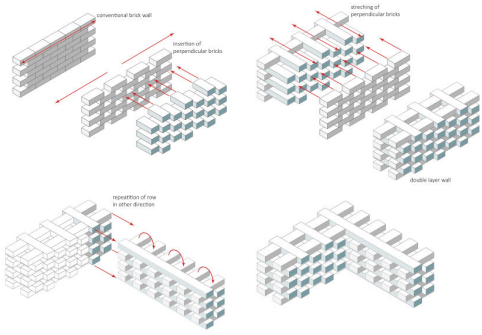



Figure 12
Modular units type A and type B with notches in different positions

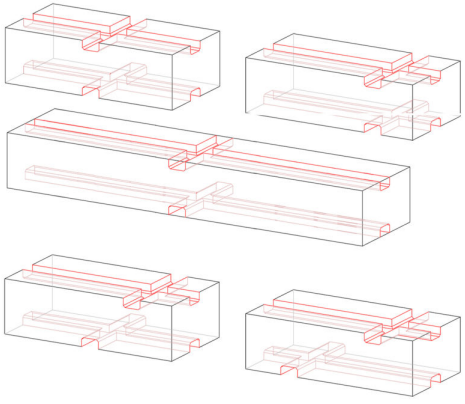


Figure 13
Addition of supporting wooden elements on a sample construction system

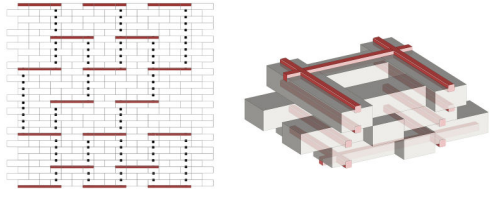
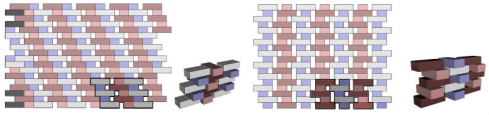


Figure 14
Characteristic wall arrangements with different openings



## CONCLUSION

This work exemplified an open-source mycelium-based material system development assisted by digital design and fabrication principles in order to achieve an effective production of various physical prototypes of modular units and construction systems. The aim was to demonstrate the material production, forming and stacking processes within an experimental context, drawing conclusions in regard to their possible application towards a more sustainable approach in architecture and construction industry.

The initial experiments and results obtained show great possibilities of their application in the construction industry due to the properties of the material under examination, which is fully compostable and its production process have almost zero impact to the environment. Obviously, issues can be discussed, which are related to the physical properties of material and, consequently, its application as a structural element in construction. The results suggest that due to its nature as a lightweight material with reduced compressive strength compared to other materials, such as clay and cement-based ones, it needs to be combined with supporting structures or reinforcement from wood or other material to achieve stability and rigidity of the systems. However, its potential use as a filler could provide more application possibilities.

Production of a specific number of elements required for a 1:1 wall arrangement prototype could highlight any inconsistencies in the material properties and reveal possible gaps in the suggested production and fabrication method. In that case, the reaction to water exposure and specific environmental conditions can be observed and evaluated. An extensive experimentation regarding its application capabilities and measurable results in terms of its ecological footprint can help towards further application and establishment in the construction industry.

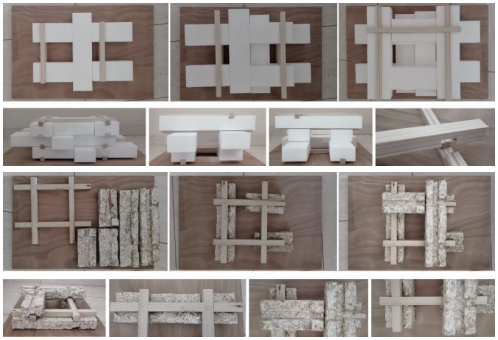


Figure 15
Physical prototype of modular brick stacking in 1:1 scale

Figure 16
Modular brick stacking of mycelium-based material in 1:2 scale

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# Life Lamp

## *Connecting Design and People Through Emotion*

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*Nowadays it is possible to use technology to achieve emotion-oriented products related to the user experience. The aim of this paper is to address a design exploration that combines the use of algorithmic modeling in order to create a design that seeks to express meaning through emotional bonds with people. Life Lamp was created to represent a life cycle as a sensitive object consisting of three layers and a unique shade that produces a complex image, expressing the paths and surprises of our existence. The design process is a hybrid between top-down and bottom-up approaches. The designers worked both with a predefined heart-like 3D model as the design base and with agent-based modeling, widely explored by Craig Reynolds in the 1980s. Life lamp is a product that emerged as a result of Estudio Guto Requena's research that investigates the impact of digital culture through design by seeking to merge technology and affection.*

**Keywords:** *3D Print Design, Agent-based System, Algorithmic Modeling, Emotional Design , Digital Design, Mass Customization*

## INTRODUCTION

Only recently, aspects of emotion have become a major issue in the design research field (Desmet and Hekkert 2009). These emotional aspects can orient the design process (emotion-oriented design) by seeking a meaningful conceptual message and can predict or influence user behavior in interaction with these products. Therefore, it is able to guide an individual towards a more conscious consumption by making design goods less disposable (Chapman 2015).

This paper reports a design process that resulted from Estudio Guto Requena's research focused on the first emotional aspect elicited by Chapman (2015). This process seeks to design and produce objects carried with meaning to an individual or a small group of individuals. According to Hekkert and Mcdonagh (2003), designers should develop products that use deeper and richer levels of emotional experience rather than just taking a short emotional response such as that generated by aesthetic or functional characteristics.

Chapman (2015) also states that we seek to consume meaning instead of matter. In other words, when customers make a choice between two similar products, they choose the one that has more existential mirrors allowing them "to view and experience our dreams and desires in real-time" (Chapman 2015). This meaning, however, can be ephemeral or long-lasting depending on a combination of individual experiences and product features.

Diderot (McCracken 1988 apud Chapman 2016) first described our relationships with products and their instability. According to the author, consumers are driven to purchase products that reflect their personalities, which means that people usually project themselves into their belongings and in the products they choose to acquire.

In this sense, we need to understand how it is possible to integrate emotional aspects into the design process by creating a relationship of identity between the product and the individual. By doing so, we allow an object to stand out from others because of its personal meaning.

While the first two levels are more primitive and immediate cognitive responses, the third level is deeper in terms of emotion and cognition. Nevertheless, a product intended to be a good emotion-oriented design must well perform through the three levels of cognition and emotion.

Thus, the self-projection alleged by Chapman (2015) could be achieved through the emotional design experience described by Norman (2004) manifesting itself in the aesthetic and functional characteristics of the product as well as in the manufacturing process, the personal meaning that it carries and/or in the philosophy of the company that produces it.

However, by analyzing current mass production culture it is possible to notice that it is extremely difficult to design and manufacture an object that takes into account individual emotional aspects, capable of creating more personal bonds between consumer and product.

The ongoing breakdown of paradigms in the design and in the production phase, on the other hand, may favor the use of particular characteristics of an individual or group of individuals in the design process. In addition to this, it is also possible to materialize this individuality in a personalized product without harming its productive and economic chain.

Currently, it is possible to rely on the use of technology to develop emotion-oriented products related to particular characteristics of a given individual (Hekkert and Mcdonagh 2003). However, personalization by itself is not enough to create emotional bonds. It is necessary to develop some sense of ownership by creating the notion of individuality or by developing some kind of emotional link between customer and product (Norman, 2004).

Desmet and Hekkert (2009) by their turn, argue that emotion-oriented design can be facilitated by bringing users to the center of the creative process. In this sense, it is possible to collect personal data that expand the capacity to generate a deep symbolism between the user and the developing product. To bring the customer into such a creative process may seem an obvious strategy, nonetheless, when the conventional productive and design chain is taken into account, it's possible to realize that several obstacles inhibit a personalized production approach.

This occurs because the conventional production chain is oriented towards a mass production system, as a way of maximizing production efficiency and, consequently, profits. On the other hand, the production chain influences the conventional design method as much as it orientates it to the "logic of repetition" (Oxman, 2006).

Having that said, this correlation makes a different design approach unfeasible. Thus to develop an emotion-oriented creative process that takes into account users' individual characteristics, it is necessary to review the productive chain system as well as the traditional design methods so that both customization and large-scale production becomes viable.

## EMOTION & TECHNOLOGY

The design of the Life Lamp was developed in such context. It was an attempt to bring an answer to these problems with innovative methods both in the design process as in the product manufacturing phase. Life Lamp's design was developed by the Brazilian architecture and design studio Estudio Guto Requena [2]. It aims to represent three main life cycles of human beings. The studio has an industry-oriented design investigation that aspires to merge technology with emotion. Furthermore, the studio features several other products that deal with the interpretation of unusual inputs of information to generate emotional value to the product. As an example, we can mention the vase collection "Once Upon a Time", which its shape emerges from audio files of a grandmother telling bedtime stories or the "Aura Pendant", in which its final shape is defined from collected personal users data, such as the tone of voice and people´s heartbeat obtained from the users while telling their love story.

The approach of capturing the user's mood through sensors and then processing this data as a means of manipulating space and objects is not a novel idea. The Life Lamp design process developed by Estudio Guto Requena´s research is similar to the explorative aspects of many installations developed by the architectural studio Coop Himmelb(l)au through the late 1960s. Moreover, the use of heartbeat data to express or generate form appears in numerous works of Coop Himmelb(l)au such as Astro Balloon and Hard Space (del Campo, 2016).

In the case of Life Lamp, it is a unique rhizome-looking object, made of three volumetric layers and a singular shade that produces a complex image, expressing the paths and surprises of our existence. The design process is a hybrid between a top-down and a bottom-up approach where designers worked both with a generic heart geometry as a surface model, as well as former knowledge about digital design using agent-based modeling.

Thus, Life Lamp seeks to tackle visceral levels of design experience by using the shape of a heart, an image usually connected to the idea of emotion, to make the first initial bond between customers and the product. On the other hand, the behavioral level is taken into account by the multiple shadows created by the three layers of rhizomatic heart shapes, generated by the agent-based modeling.

For this, parametric and algorithmic design techniques were used to define a form generation strategy. The morphology aspects of the lamp were parametrically linked to specific heartbeat sound data collected from a group of three individuals and converted into numerical information. In this regard, the heartbeat audio file was used as a means to interpret a physiological phenomenon as the symbolic expression of a human feeling. Therefore, it was possible to materialize this interpretation of emotion creating a direct link between product and individual.

By using such personal data as design inputs, the reflective level of emotional design was carried out by strengthening the relationship between the individual and the product. It creates the possibility to evoke good memories of the participative design process. If the individuals from whom the heartbeats were collected are friends or members of the same family, it is expected that these memories will have a greater impact as it may evoke good feelings.

According to Rivka Oxman (2006), digital design is a non-standardized, non-normative, and nonrepetitive approach developed primarily in the computational environment that contrasts the normative productive logic of industrial modernism. To this author, digital design challenges the productive demand for repetition or standardization (Oxman 2006). Thus, digital design proves to be an appropriate approach to develop a design strategy that seeks to create a deep emotional link materializing a product that incorporates individual and sometimes intangible affective characteristics.

Concerning a broader and more participatory process by the consumer in the creative process, David Benjamin (2012) believes that digital design, supported by the use of parameters and algorithms, has the potential to democratize design. It allows

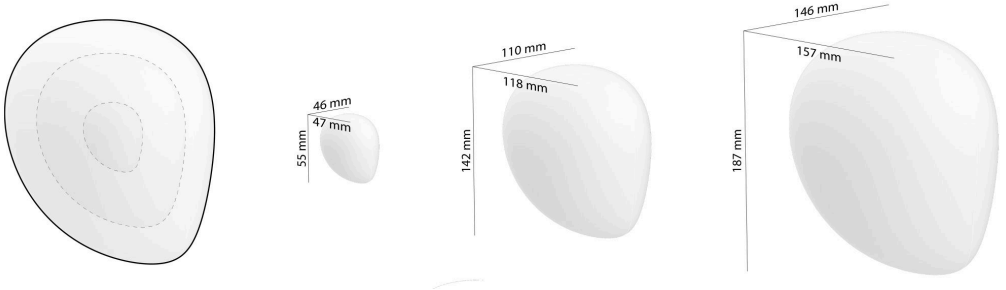



Figure 1
Concentric heart geometries and its dimensions.

the participation of other individuals involved during the creative decision-making process. This is possible due to the nature of digital design that seeks, with an algorithmic description of the process, to determine the relationship between different characteristics of a design. Since the characteristics of a design piece are described this way and are linked in an algorithmic process, it is possible to test several design possibilities without the need to develop a new design from scratch at each iteration. Thus, it is also possible to describe a single design process that uses data from different people and resulting in a unique product for each data received.

The ability to make design artifacts that meet individual demands at a competitive price and production time is called mass customization (Phua at al 2007; Tseng et al. 2017). In this paradigm, each customer must be considered individually, providing personalized products and services based on an agile, flexible, and integrated process of the product's life cycle (Tseng et al. 2017). Thus, in the manufacture of the "Life Lamp", in order to personalize the product according to the individual's characteristics, a file-to-factory fabrication process was used. Once the virtual modeling of the lamp was completed, the file was sent to a 3D printer capable of printing the product in its morphological specificities. Both design and production processes were able to collect personal characteristics from different individuals and manufacture a customized artifact without harming their production chain.

## SYNTHESIS & REPRESENTATION

An existing computational method for data and information processing is the agent-based modeling (Gilbert 2007). This method is capable of integrating material organization, design tools, and contextual environments as guidelines in a bottom-up design process in which the self-organization of the processing devices generates adaptive behaviors to explore emerging and unpredictable complexities (Baharlou and Menges 2013). Used in several other scientific fields, the agents are usually taken as autonomous and adaptive elements (Baharlou 2017) that are capable of computing the environment and are used to process and synthesize several natural phenomena. They are mostly used in computational simulation of events of the physical world and are capable of representing phenomena or systems for experimentation or construction of scenarios (Gilbert 2007).

This computational method considers the adaptive interaction in a collection of several autonomous decision-making entities (Bonabeau 2002) that follow simple local rules and interact with a given environment (Gilbert 2007). The emerging collective behavior is different from the behavior of individual parts (Holland and Miller 1991), thus, the global behavior arises from a set of rules that defines the agents' strategies in recurrently new environmental conditions (Holland 1995). Such a set of rules also defines the behavior of agents and guides decision-making processes, where agents are able to modify the previous set with new data acquired from the

environmental context, altering and devising new rules (Baharlou and Menges 2015 and Casti 1997), which promotes the occurrence of dynamic adaptations (Baharlou 2017). Therefore, a behavioral system emerges from the organization and adaptation of individual and collective behaviors, in which the agents mediate the process of form and material synthesis (Baharlou and Menges 2015).

The agent-based modeling was used as a means to process the emotional data with a form-finding digital approach over three predefined concentric heart shape geometries that were scaled up according to the different life stages of three individuals: a newborn, a 30-year-old person and a 70-year-old elder. Considering the heart rate difference among them, their heartbeat sounds were collected individually, resulting in three different audio files. The volume peaks from the audio files were extracted and converted into binary data. They were taken into the design process as input parameters of the behavioral algorithm of the agent-based system. The control of the behavioral parameters by the audio files was a design strategy that allowed variation, non-deterministic occurrences, and integration and synthesis of the sound data as a geometric representation during the form generation process.

In addition, the feature of data processing with an emergent design approach, the Agent-based method was chosen due to the similarity of the observed design applications to natural branching systems, such as the vessel system that carries blood throughout the human body.

## DESIGN METHODOLOGY

### *BASE GEOMETRY*

The lamp design was defined on top of this briefing that guided the whole development. From this framework, the aim was to somehow interconnect three different heartbeats and the three concentric heart shapes in such a way that the heartbeats would dynamically change the final output.

There were six main steps in this process, first, the geometry of three hearts were modeled using traditional form-making digital techniques. The small one with a bounding box measuring approximately 46 x 47 x 55 mm, the medium-sized one with 110 x 118 x 142 mm and a large with 146 x 157 x 187 mm, although the medium-sized heart was the only one close to the dimension of a real heart (Figure 1).

### *HEARTBEATS*

The second step was to record three different heartbeats and then denoise the recorded .mp3 file using the software Adobe Audition to achieve a sharp heartbeat sound separated from breathing noises or, in the fetus case, all amniotic fluid noises.

### *AGENT-BASED SYSTEM*

The next step was to deploy a generative system using the Grasshopper add-on called Culebra 2.0, inside Rhinoceros 3D modeling software environment. This system used the same algorithmic steering behaviors like the ones developed by computer scientist Craig Reynolds in the late 1980s (Reynolds 1999). The final geometry, however, used only the trail created by the agents' paths, and not the agents themselves.

Culebra 2.0[3] was essential in this step as it already had many pre-configured behaviors with a user-friendly interface from which four of them were used: the "Mesh Crawl" behavior that constrained the agents to move only on the surface of the heart geometry; the "Weaving Wandering" behavior that made the agents weave around its established direction giving a weaving pattern to the resulting trail; the "Flocking" behavior which made the agents interact with each other in a similar way to how birds interact in a real flocking; the "Stigmergy" behavior that made the agents interact with the trail produced by other agents. All of those data behaviors configured Culebra 2.0's main component "Creeper Engine".

Apart from the steering behaviors, the setup also had a hierarchy of two groups of agents, the parent-agents and the child-agents. The parent-agents stayed the same through the whole process of design, while the child-agents spawned from the parent-agents and had a short lifespan controlled by the heartbeat sound.

### *INTERACTION*

The interaction of the agents with the input sound of heartbeats was achieved using a speaker that emitted the recorded heartbeat sound and the Grasshopper add-on for interactive prototyping Firefly (O Payne 2013). Through Firefly's component Sound Capture, it was possible to receive the signal of the computer microphone and directly analyze its volume. Additionally, using a simple *if* statement inside Grasshopper environment, the algorithm checked each time the volume was higher than an established threshold, consequently, it was possible to create a *true* and *false* boolean data type that followed the rhythm of the analyzed heartbeat (Figure 2).

When the boolean data type is set *true*, the algorithm sends the location of the parent-agents to a second Culebra 2.0 Creeper Engine with different values for the aforementioned behaviors, releasing child-agents from the same place where the parent-agents are located. Those child-agents, however, survive for only one complete cycle of a heartbeat. As the first group of children dies, their paths are recorded and then a new group of children spawn and so on. Consequently, the child-agents created short, secondary paths.

With the environment and behaviors defined, 57 parent-agents were released at the same location, the highest point of the smallest heart geometry. Then, the heartbeat sound of the fetus activated the spawn of child-agents.

As all the agents interacted, their behavior made them avoid proximity with each other and all formed trails, while at the same time they were gravitally bound to the geometry. Thus, it created distinct paths on the surface of the geometry that seldomly overlapped, creating a vessel system appearance to the final design.

### *HUMAN-MACHINE COLLABORATION*

As the parent-agents converged at the bottom of the small heart geometry, the algorithm had to be paused for the designers to change the heartbeat sound from the fetus to the adult and also the heart geometry from the small to the medium size. As a design decision, the number of parent-agents was decreasing, going from 57 to 36. This process was repeated in the next iteration, and the number of parent-agents was reduced again, now from 36 to 27. Although the parent-agents had their number reduced in each iteration, the remaining ones created seamless bridges between the heart geometries, which made it possible to have one continuous path for the whole lamp (Figure 3).

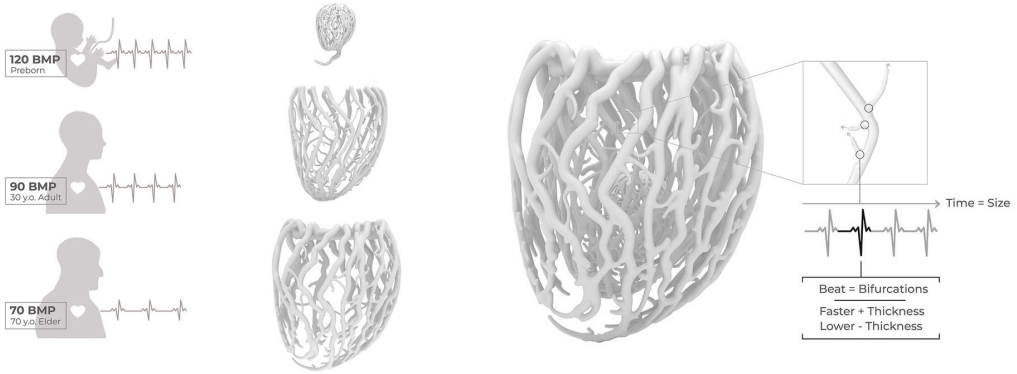
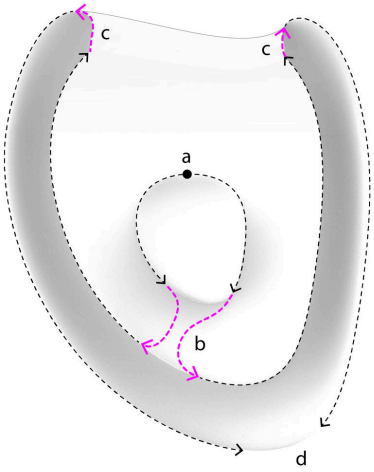
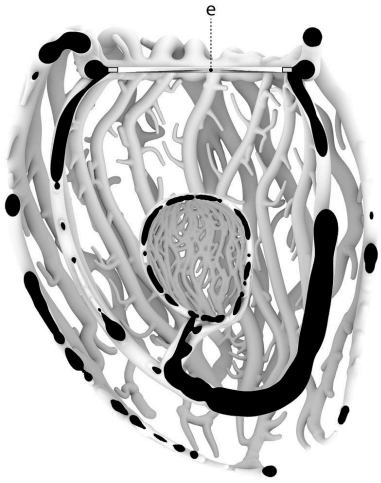



Figure 2
Simplified commercial diagram summarizing the form generation.

Figure 3
Trail paths diagram:
a. Spawn location;
b. Bridges connecting the small and the middle geometries;
c. Bridges connecting the medium-size and the big geometries;
d. End of agents trail paths. Section:
e. LED Lamp Support was given by Decimal [1].




### *MARCHING CUBES*

The parent-agents generated 23.7 meters of trails, while the child-agents generated 30.5 meters, adding up to approximately 54.2 meters. The next design step consisted of thickening the resulting trail paths. To do so, the most appropriate method was to use a Marching Cubes algorithm by the Grasshopper add-on, Cocoon. This algorithm was initially developed to process 3D medical data such as computed tomography (CT) and magnetic resonance (MR) achieving inter-slice connectivity and generating a surface reconstruction (Lorensen and Cline 1987). This algorithm was crucial to producing a single watertight mesh geometry ready for 3D print, which was the final step of Life Lamp design.

The variation in thickness was achieved through manually inputting custom values into Cocoon, aiming to have a slender path in the small heart, and a thicker path in the biggest heart. It was also really important that the paths had a tapered shape with a smooth transition (Figure 4).

### MATERIALIZATION

As digital tools provide us with a four-dimensional space-time blank sheet, the gap between reality and digitally constructed concepts has to be linked. Such a link is possible to be achieved using digital fabrication processes. Powerful tools capable of turning binary codes into physical spaces are bridges that bring us closer to the images that we create in our heads.

To bring Life Lamp to reality, a range of possibilities inside the digital fabrication domain was possible to be used. Starting with Fused Deposition Modeling (FDM) - a common one in digital manufacturing. However, due to its intricate geometry, too many supports would be necessary to structure its rhizomatic branches. It would demand an extra manual step into the production process to remove these structures and clean up the object, which would certainly interfere with the product viability.

On the other hand, considering a Digital Light Processing (DLP) production approach, it would be possible to print the entire piece using less support compared to the FDM process. However, some supports would still be needed to structure the object. This dependency would make the manufactur-

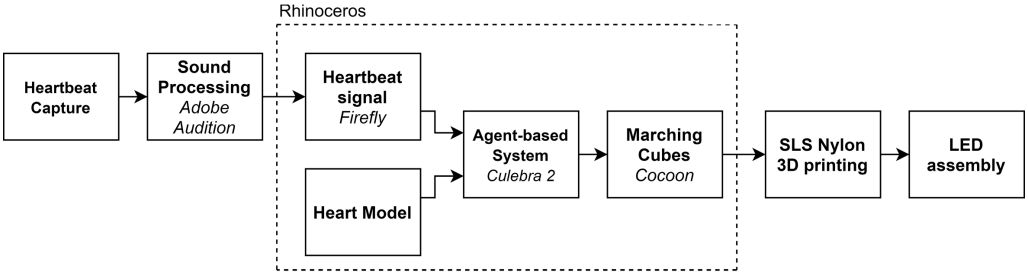



Figure 4
Flowchart with the complete sequence of creation and production.

ing process more complicated since accessing the central layer - the one that represents the newborn heartbeat - without damaging other parts of the object would be practically impossible or too difficult to manage.

These production and viability constraints had led to the choice of the Selective Laser Sintering (SLS) process. Similar to the DLP process, in which liquid resin is cured layer by layer, this method uses a laser to cure plastic powder, layer by layer, to build its parts. As each cured solid plastic layer lies over the reminiscent powder, there is no need for support (the reminiscent powder works as a structure) and this complex rhizomatic object with its multiple strati could be produced and printed at once. Without the addition of a manual process, it was possible to give more freedom for design exploration and fabrication.

## CONCLUSION

By analyzing Life Lamp design process it is possible to state that the use of novel technologies can favor the creation of emotional bonds since it is capable of bringing personal characteristics from individuals into the products. This way, by stimulating the reflexive level of the design experience process, it is possible to create a longing-last relationship between user and product by creating a sense of ownership when projecting a user's self-image on the design process.

As a product that communicates a symbolic message, Life Lamp reveals itself as a dialogical object, translating graphically parameters that every single human being presents during its lifetime. It is a draft in essence. A three-dimensional geometry based on an interpretation and symbolic representation of human emotions as numeric parameters, carefully organized to form an object/icon, which ultimately conveys a meaning. The message (the human life cycle, the complexity of its layers, and the beauty of its finitude) and the medium (the object - lamp) are merged into a single element. In this way, the lamp becomes the means of propagating this message.

Considering the reason for the object's raison d'être, which is the propagation of the message, Life lamp is an experimental design object in its initial phase. Employing parametric design and algorithm modeling techniques, it is possible in further developments to add new parameters to this to evolve this design process. As long as the design research keeps on moving into the field of human emotions discovering how to measure them (and transforming this information into input data), it will be able, to physically materialize them or, in other words, sculpt emotions. Like a genealogical tree that describes the connection among members of a family, Life Lamp may become the symbol of a family's affection.

That opens space for mass customization in the material sciences field, simply because every single human being could have their own Life Lamp, each one with its particular features, special shapes, and scars. In the digital age, mass customization means that this customized product will be produced through digital fabrication, which in turn allows the decentralization of production. The result would be a customizable product that reinforces human iden-

tity as a species and can be produced independently by each community. This experience would not have an end in itself but could become a model for further experiences on how to spread affection across emotional consciousness around society.

## ACKNOWLEDGMENTS

Thanks to Estudio Guto Requena and Decimal.

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Figure 5
Life Lamp on.

# Growing Construction Components

## *Design and simulation strategy for self-formation following tree growth*

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*Driven by the statement: what if buildings could think, this work continues with another inquiry, what would happen if the building elements knew how to grow, regardless of the material they are made of, or if that building could respond throughout history to different challenges or structural needs. Therefore, this paper considers studying other structures evolved in time, such as trees and their predefined laws of growth. The construction elements could then be developed, responding to future scenarios, having the capacity to grow in volume, conserving their material properties, as a dynamic organism. This work presents a parametric approach, which, with the help of FEA, will stimulate the growth of the cross-section of a tree stem as if it were the cross-section of a building element.*

**Keywords:** *bionic, growing, aided tree growth, optimization*

## INTRODUCTION

The necessity to optimize the use of the limited resources of our environment encourages areas such as architecture and structural engineering to make designs with more efficient use of materials. The simulation of structural behavior becomes a relevant tool based on an iterative process of design and analysis. Multiple computational design features enable the generation of mechanical elements with optimized geometries and the manufacture of objects with high precision in specific utilities, acquiring a great certainty of how the material would behave in limited situations. Nevertheless, from the moment of its manufacture or assembly, the construction element loses its computational component, so its design constrains cannot be longer altered. That element stays as a physical object with constant properties over time. In most cases, they remain unalterable, depending on the climatic conditions and the obsolescence of the material. However, natural structures and specifically trees, have the capacity of self-formation, responding to particular situations, always in the correct way by body map.

### *Nature as a model*

Taking nature as a model has been a recurrent strategy to apply knowledge in different disciplines. In the last two centuries (Goethe, 1790) (Darwin, 1862), natural organisms began coming across as dynamic beings, which have an accumulation of variations over time and can adapt. The ability of organisms to change their shape as they grow is a field that has been continually studied by biologists (Thomsons, 1917). More recently, through computer science, it has become possible for areas such as biotechnology to emerge and become state-of-the-art. The design

process, combining simulation strategies, becomes a transdisciplinary process.

The elements that compose the architectural structures are static components from the time of their manufacture. However, this assumption could be different in the case that a variation in time was possible; for example, by using elements based on living elements. What if they could modify its morphology, change its functionality, respond to external conditions, structural requests, deposit/relocate material, or grow in the volume where it is necessary, in a precise moment. Then the computational capacity of a construction element remains; that is, it could change once it is part of a building (Figure 1).

### *Aided growth*

Outside the field of construction, we can see numerous examples based on guided growth with trees (tree shaping), where branches, trunks, roots even today continue to adapt to changes in the environment, displacing their biomass over time. This brings us to a more detailed analysis of how to imitate the topological growth of trees by computer. How to guide it and how to predict the movement.

The starting point for this work is the isolation of these tree components to transform them into three-dimensional models where we can make previous modifications and observe how their geometry adapts. Their growth generally falls into two categories:

- Branching, the ability to generate new elements, i.e., the main lines that follow in its length, which can be disrupted by external factors (tropisms), or even can be aided.
- Self-formation, how these elements generate more resistance in order to meet the requirements of the guidelines.

This paper will focus primarily on the second. We will present how trees can acquire greater struc-

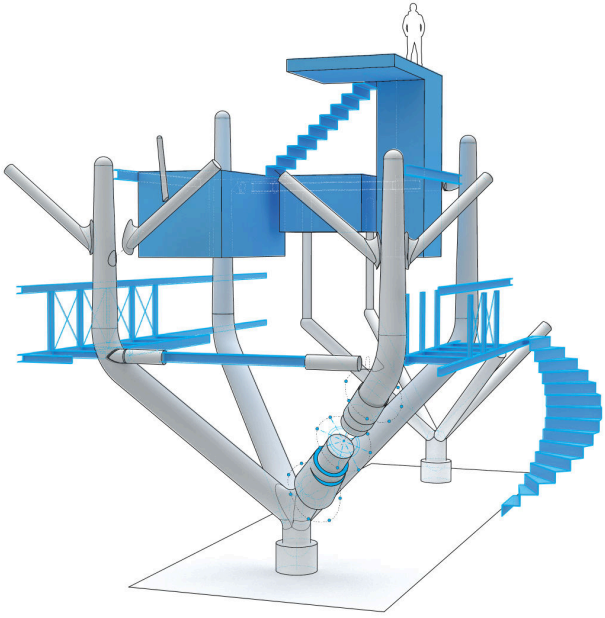


Figure 1
Growing structure concept

tural strength in their cross-section and address this through an iterative process.

## LITERATURE REVIEW

### *Observation, understanding, and adoption of self-formation processes in nature*

Observing biology and natural phenomena have always been an elementary resource of experience and knowledge. Nature served and still serves either as a model: for imitation ('Mimesis' = > biomimetic); as a basis for the structuring and construction of human artifacts ('Basis' => biobased, bio-structured); or as a system whose products are used to create artifacts ('Genesis' => biogenetic, biobased) (Trautz 2015). Euclid already understood nature as the most critical source of manifestations of mathematical laws. Natural processes, organs and natural structures such as the flight of birds, the respiratory organs or glands as well as skin or leaf surfaces served as models for technical solutions for flying, the construction of air or fluid transport systems or the design of surfaces with reduced flow resistance or maximized surface tension (lotus effect). The early inhabitants of Scandinavia, Vikings, used curved parts of trees, such as branches or the roots, as building components for their ships. Lately, in the 19th century, the Catalan architect Antoni Gaudi studied biological forms and their repetitive nature to stimulate modern constructions. He considered the structure (trunk) of a tree as a perfect adaptive structure (Barrallo et al. 2011).

Since 1960, the architects Helmcke and Frei Otto have been concerned with natural processes of self-formation on very different scales. They studied these processes from the formation of small organisms and bone structures to architectural and urban morphologies and the formation of networks of paths. The work of Frei Otto and Johann-Georg Helmcke established a basis for the Collaborative Research Centre 230 'Natural Constructions' in 1984 (Otto et al. 1982, 1984) at the University of Stuttgart. The idea was to combine biology and technology and to provide a common platform for interdisciplinary discussions (Knippers et al. 2016). In the SFB 230 principles, strategies and models in nature were worked out and verified with technical tools.

### *Tree-like structures and living constructions made of woody plants*

Otto's work also led to the development of the "tree-like support structure," which later found its way into architecture. In these examples, they graduated cross-sections according to stress, without explicitly considering bending, and taking the plane of the roof as a common connecting element.

Within the last decade, "building botany" experiments appears as a new discipline on a kind of plant construction design (Ludwig 2012). Under controlled conditions (e.g., water balance), multi-story buildings were partly constructed from living woody plants. In the process, mixtures were also created by bringing together artificial building components with living ones and by forming a form-locking connection with them as they grew. Results are pending, due to the slow growth of plants and the slowing down with increasing plant age.

### *Self-optimization and the structure of trees*

A significant contribution to the study of trees and optimization comes from Claus Matteck (et al. 1998). In addition to the original research team with Lothar Wessolly (et al. 1991), Mattheck developed five sets for self-optimization of trees: a) Trees minimize stress by reducing the loaded lever arm, i.e., by changing the growth pathway. b) Adaptive growth reduces stress concentrations. c) Wood fibers lie along with the force flow, minimizing shear forces between fibers. d) Wood strength adapts to the degree and type of load. e) Growth stresses counteract critical (external) loads. The strategy of a tree to reduce stress peaks postulated here was used in other areas of engineering, in computer-aided optimization as 'CAO' or 'soft kill option.' These biomimetic structural optimization methods, defined in DIN ISO 18459 (Mattheck et al. 2016), aim to modify the shape and topology of the technical components and thus homogenize the stresses using finite element analysis (FEA).

Several species of trees respond differently to applied loads, tension, or compression. As a result, conifers and delicious trees generate compression wood and tension wood, respectively. Since the 1990s, research has focused on the origin of the reaction wood and its relationship to cell composition and structure (Goetz 2000).

Besides, Lindermayer-Systems supported the branching strategies and contributed to the computational design of trees and fractals (Prusinkiewicz 1990). The L-Systems also give the possibility of generating digital models in which to include the self-forming of a structure. The work carried out at The Chair of Structures in RWTH Aachen previously applied this concept in the optimization of tree structures (Pranjic 2018), where longitudinal growth is related to growth parameters, such as tropism, with the mechanical analysis through FEA, generating a simulation of self-formation in the branch of a fir tree. Following an incremental procedure, by iterations, the generation of the geometry followed static analysis and shape optimization in the branch cross-section.

## METHODOLOGY OF GROWTH SIMULATION

The methodology of analysis begins by abstracting a longitudinal tree stem and locating, which are the determining factors that apply (Figure 2).

During the process of their growth, woody plants respond to the effect of dead weight and the increase in exposure tasks associated with growth, such as increased loads due to wind, presence of fruits. This model aims to simplify these external agents and focus on the generation of this computational work, which can later include more conditioning factors so that we will consider only the own weight as a loading.

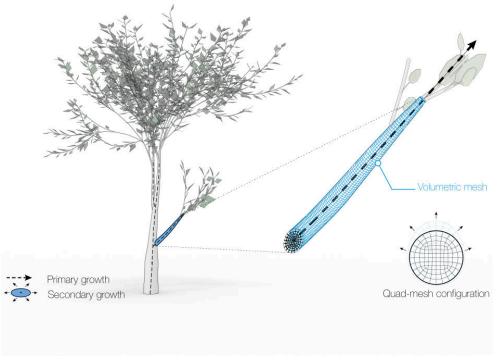



Figure 2
Study of the growth of a tree branch.

The process of structural self-formation has two dimensions of growth:

- First, the primary growth or global growth of the branching organism (L-System) and the reaction to tropisms; this model will evaluate only this growth in length of its axis.
- The secondary growth considerate the load as a local input and changes its shape and rigidity distribution in the cross-section.

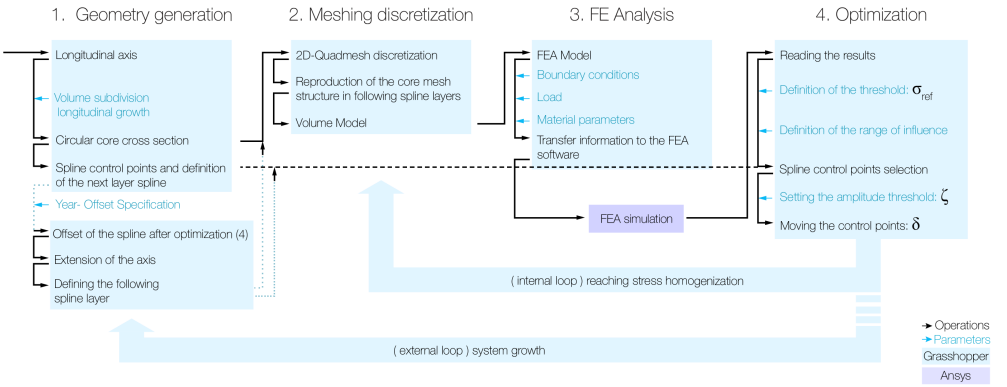
### *Growth optimization procedure*

To carry out the optimization process, we focus on the increase of geometry and, therefore, material that varies along the growth axis. To map this growth, we distinguish a series of rings, as annual rings, which distributed along the main axis.

The main axis is the so-called guide axis, which we will take as a straight line that grows in its length in a horizontal direction. However, it could be replaced by another curve that responds to external factors, such as helium-tropism, or simply aided by own interests.

These rings allow us to store the sequence of growth states, that is, each iteration of growth; that is, each annual ring would be optimized at a specific time, with determined characteristics, and with specific loads and boundary conditions.

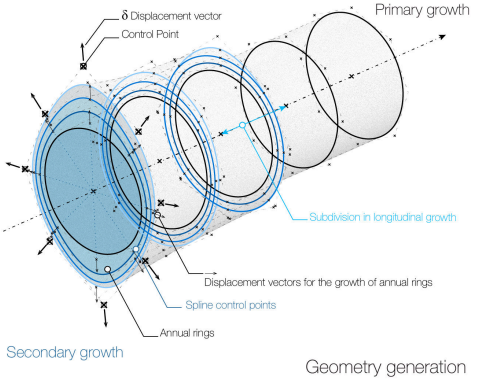
Figure 3
Workflow

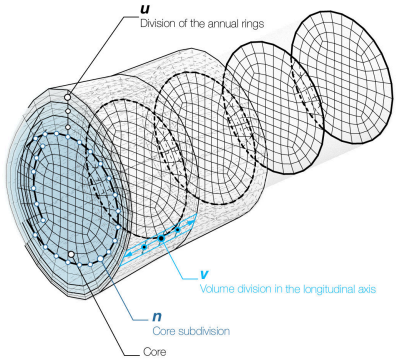



The analysis and optimization of this geometry take place in a loop procedure using the parametric modeling software and the development platform Grasshopper (Rhinoceros) in combination with the FEA software Ansys, and the shape design and optimization through stress following Eq. 1 and Eq. 2. The calculation cycle developed with these tools includes the next four sub-processes (see Figure 3):

1. The initial volume (Figure 4) is generated from a main axis and a series of sections. This axis is subdivided along its length, defining the separation of the core sections. Next, it performs further offsets of these cores to determine the annual rings based on third-degree curves. These curves follow a certain number of control points to be able to manipulate them later in 4).
2. Based on the geometric information of 1), the discretization/meshing takes place for the following FEA analysis. For this purpose, the core sections here are discretized into a 2D quadrilateral mesh with n- core subdivisions reproducing the structure with u- divisions to the next growth rings, and finally in the following spline planes in the axis length with v- volume divisions (Figure 5).
3. We collect the nodes, elements of the mesh, establish the connection information of these nodes, as well as the necessary data for the calculation (support parameters, load, material) and transferring them to the software Ansys.
4. In the optimization component, we sort all nodes that exceed a specific threshold value by a defined amount to optimize the geometry so that the cross-section in the area of these nodes increases. To do this, we classify the nodes and select the splines control points (1) closest to these nodes. A growth vector defines the new position of these control points, causing the section to increase.

Figure 4
Geometry generation from splines with control points, and additional growing rings






Mesh generation

Figure 5
Mesh generation: Cross-section as a Quad-mesh and continuation of its topology to the following rings, and discretization of the volume replicating the structure in the length axis.

### *Iterative process*

Steps 2 to 4 repeat (internal loop) until the stress in the entire structure falls below the defined threshold value (Eq. 1) and achieves a stress homogenization.

The displacement vectors (Eq. 2) make modifications to the splines, which in turn modify the mesh configuration, and transfer the information to Ansys.

$$\min_{x \epsilon \Omega} \frac{||\sigma_{vMises} - \sigma_{ref}||}{\sigma_{ref}} \quad (1)$$

$$\delta = \frac{||\sigma_{vMises} - \sigma_{ref}||}{\sigma_{ref}} \zeta \quad (2)$$

This information transfer continues in the background through Grasshopper, which translates geometric information into points, and mesh elements. The execution of the analysis is also automatic from Grasshopper using a developed plugin that sends and receives the information, making Grasshopper the main generator and interpreter of information.

This loop also bakes the final state of the shape optimization, i.e., the initial growth ring, and takes it as a starting point for the next iteration process.

When the algorithm completes the inner loop, the calculation cycle starts again with the generation of the next growth ring (external loop), remapping the structure again. It offsets the previous splines, and a new geometry goes through the optimization process (internal loop), in which only the most outer rings optimize their shape sequentially.

This process mimics natural growth by studying the proportion of biomass added in the radial and axial directions and sorting that as different layers of growth.

## RESULTS OF GROWING SIMULATION

According to the previous workflow, we simulate and test this procedure, in which we differentiate three growth configurations to compare: a growth based on a static structural optimization 4.1, the growth based on the material characteristic of the trees (reaction wood) 4.2, and the simulation with the distinction of material resistance 4.3.

### *Static shape optimization*

We execute the algorithm as if it were only a pure static optimization, that is, the control points vary freely their position in the plane of each cross-section.

Following the workflow, we set up a test with a 30mm core and a length of 1000 mm (Figure 6), and we limit the cross-section growth up to three rings and longitudinal growth 100mm with each workflow external loop. The iterative process finished showing a result of an oval geometry (Figure 7) that tends towards rectangularity, with a relatively flat top and bottom. Comparing the results of the FEA of the initial state and the final state, they show a reduction of the maximum stress, with a trend of reduction in the edges.

### *Shape optimization based on tree growth*

In the second test, we restricted the growth according to the material property, i.e. as if a conifer was addressed, and generated reaction wood as a compression wood that meets the mechanical need. For this reason, we restrict geometric generation, only permitting the control points located in the lower half to move freely.

Figure 6
FEA model based on solid elements. Simulation of initial steam core (t=0)

Comparing both tests 4.1 and 4.2, we can observe that t=3 reduced the cross-section stress up to 67% and 54%, respectively, compared to the initial geometry t=1, even though the stress had successively increased due to length growth.

### *Variable stiffness distribution based on tree growth*

In this phase of work, we complement the last form-optimization with the variation of the rigidity in the cross-section. For this process, we establish a simulation taking as an example, the geometry generated from 4.2 coniferous wood, in which the density and modulus of elasticity vary within the cross-section (Figure 8, 9).

Figure 7
Static shape optimization (t=3)

According to the proportionality of density and stiffness in wood, Young's modulus and density graded in a linear correlation in four sizes (number of cross-sectional particle areas/rings). The stiffness correlation was based on values from Goetz (Goetz 2000) for a mature tree with a stiffer core or mature wood and the less stiff sapwood zones.

Figure 8
Simulation results, optimization of a softwood cross-section considering the reaction wood in compression

A comparison of mass and stress between the cross-sections with constant and variable material stiffness shows a weight reduction of about 40% and a stress reduction of about 45%. Depending on the gradation of stiffness, we can see that the greatest stresses occur in the core, i.e., a large part of the load is transferred through the core. The higher deformation of about 50% with a lower weight indicates a more flexible design than with a cross-section with constant stiffness.

## NEXT STEPS

The project schedule includes the incorporation of more external parameters and environmental factors in the workflow, and freedom to simulate other growing curves.

Figure 9
Optimization result by taking the geometry of Figure 8, and establishing different material stiffness

In 4.3, we observe how structural performance varies with different material properties. In future phases, we will attempt more accuracy in the variation of stiffness as well as incorporating plasticity as a material parameter.

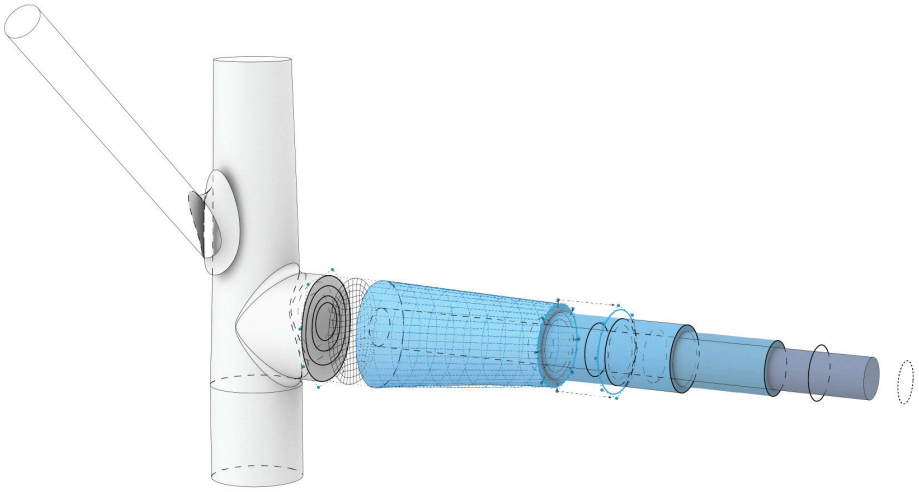


Figure 10
Integration of a pseudo constructive element, following the rules of natural growth.

Finally, we will evaluate this tool as a benchmarking with plants growing freely and assisted plants during their growth.

## CONCLUSIONS

This paper presents an approach to a shape optimization tool, integrated into a workflow that allows simulating the three-dimensional growth that would make a tree considering its weight. This tool shows three scenarios: a simulation in which we show the optimal geometry without specific properties of tree growth, and two approaches on a hypothetical softwood tree.

This tool brings close to foresee how the secondary growth of the trees would behave, and what their resistance would be. On the other hand, the workflow separates the data entry of the primary and secondary growth; this can be used to simulate how would perform with the expected primary growth or with a manipulated/assisted direction.

This work does not intend to demonstrate what construction applications can be made. However, it does demonstrate the possibility of making an iterative study of the growth of that construction, which remains dynamic over time, making use of a smart material which performs self-replication, self-regulation, and self-healing.

The project also opens up other possibilities, such as applying the workflow to other natural organisms. Alternatively, in reverse engineering applications, we can use it to improve or restore existing constructions with additive technology, increasing resistance through layers with specific properties where necessary.

The study of the evolution and growth of structures over time becomes a subject of collaboration between biologists, engineers, and designers.

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# Dynamic Relaxation Simulations of Bacterial Cellulose-based Tissues

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*In this paper, a sample of a bacterial cellulose-based tissue is studied in terms of its tectonics by presenting a framework that proposes a transition from digital to physical in terms of design and fabrication. First, sample tissue is digitally modeled and optimized through dynamic relaxation of spring-particle systems by simulating bending behavior; secondly, the tissue is materialized in a form of a biocomposite out of plant cellulose as a fabric out of fiber network for reinforcement, and bacterial cellulose, as the membrane. As the last step, the results are discussed in terms of the deflection, tensile stress lines and bending moment. This framework anticipates a number of methodologies from design and biology, combined with digital fabrication technologies in new ways to change the processes, augment the quality of ideas and outcomes; thus, question the perception of making spaces for living.*

**Keywords:** *Structural optimization, dynamic relaxation, bacterial cellulose, biocomposite*

## INTRODUCTION

"Growth" is the key concept of genetics applied to architecture and design, responding to ever-growing environmental hazards. In terms of manufacturing environmentally friendly products, biologically active materials are currently under discussion. The aim of this paper is to investigate the cooperation of nature and architects through materials found in nature with the help of advances in digital fabrication technologies. In this regard, bacterial cellulose-based tissues are studied in terms of their tectonics in order to question whether we can replace building materials that are non-biodegradable and harmful to nature. The methodology involved the use of digital design and fabrication methods and tools for the explorations on the dynamic relaxation simulations for bacterial cellulose-based tissues. The use of catenary structure for such a material that is relatively new to the structural use has proven effective as a design prototype because of its ability to self-stand and to biodegrade. The findings show that the dynamic relaxation simulation and compression test have both differences and similarities. While the deflection, tensile stress lines and bending moment were defined at the simulation, it was seen that the compression test has also resulted with the same deformations on the overall form. On the other hand, while the simulation was far preciser in terms of mathematical accuracy, compression test only provides evidences based on observations. In overall, the implementation of the transition from digital dynamic relaxation systems to behavioral systems was successfully conducted.

## THEORETICAL BACKGROUND

Nature's survival strategies are based on sustaining life with minimum resources and maximum performance (Oxman 2012). These strategies involve various mechanisms such as growth, response, action and reaction, evolution, mutation, adaptability or natural selection. As one of the results, maximum diversity is achieved with minimum inventory from a biomechanical point of view (Pearce 1981). Since nature relentlessly evolves, each unique characteristic of biological materials and structures tends to adapt itself to the environmental conditions (Koch, Bhushan and Barthlott 2009) such as self-cleaning feature of lotus leaves, strength of bone structure, or color change and light absorption of butterfly wings (Forbes 2008).

As seen in nature, the Parthenon, the Eiffel Tower or the Golden Gate Bridge are all great examples of what is possible with a particular material in manmade structures. In these examples, the forms are the direct outputs of the material selection by necessarily taking material properties into consideration (Ashby and Johnson 2007). Another earlier example is Frei Otto's physical form finding method in his work "Tensile structures: Cables, nets and membranes" (1972) "minimal surfaces with minimal nets" were calculated through mathematical equations in an experimental setup.

During the last two decades, as happened in the Industrial age, not only what we design and manufacture; but also, how we design and manufacture have changed. While before the form was being influenced by the nature of material, today, with the advanced technology, nature of material can define the form. However, while the understanding of materiality shifts from conventional materiality to new materiality, form generation also differs in each understanding. Form-making process is entirely contrasting to the process of form finding.

The omnipresence of computational tools has encouraged a culture of making in which if an object is able to be design, then, it can also be built. In this conventional approach, material waste is higher compared to the outcome of form finding processes since form finding processes are as natural as the design problem (Oxman 2007). This new materiality approach utilizes several type of form-finding processes that allows designers to explore the nature of material; in other words, what a material wants to become.

Form finding processes including material behavior studies, which actually date back to the 1970s, and even before in Gaudi's catenary curves to design vaults, have become a focus again in design studies (Otto and Nerdinger 2005). Developments in biology and material sciences started to be considered as fundamental sources for advanced material design (Thom 1975; Ruse and Hull 1989; Paton 1992; Bar-Cohen 2006). Growing interest of designers in the developments of biological and morphological structures has brought about a new materiality approach based on organic, degradable, renewable and recyclable materials to be used without reinforcement or in a composite form.

By constructing the foundations onto the new materiality paradigm, that prioritizes the material itself, this research inquiries into an experimental process of biologically inspired design and digital fabrication. Bacterial cellulose, a microbial polysaccharide, have found to be a proper source of knowledge and a morphogenetic model for design applications due to its material properties such as its structural integrity, hydrophilic nature and biodegradability (Fernandez 2006) although the use of bacterial cellulose as a biologically active material for design and fabrication is still in its infancy, yet has a potential to be further explored.

Corresponding to this new materiality paradigm, a similar approach is presented in the physical and digital realm of this research, considering the processes as form finding processes in which material behavior and performance were simulated. There are three main steps: In the first step, bacterial cellulose was grown up to a certain point where it reached a convenient workable surface area and thickness; as the second step, plant cellulose tissues and their structures were examined; in the third step, a sample

of bacterial cellulose-plant cellulose tissue was modeled and simulated in digital and physical realms as a composite tissue. The methodology was given in detail at each step. At the end, the results and potentials were discussed.

## DYNAMIC RELAXATION SIMULATIONS

### *Reproduction of bacterial cellulose*

Bacterial cellulose was obtained from a symbiotic culture of bacteria and yeast (SCOBY) culture which consists of cellulosic fiber structures that are used as an ingredient in the process of fermentation and reproduction. Characteristically, it is dense, round, rubbery and opaque (Dutta and Paul 2019). In order to work with the culture, several steps were followed for cultivation. For the exploration of bacterial cellulose, first, a mixture of water and sugar, was prepared and heated. After the infusion, culture was poured into the sugary 20cmx20cm container, and covered. It was left for fermentation for 8 days at room temperature. After fermentation process was ended, the bacterial cellulose culture has reached to a workable surface area (same as the container surface size) and thickness (1mm) after 14 days.

### *Plant cellulose-based tissues*

Plant cellulose, discovered in 1838, is broadly used for paperboard and paper today. Earlier forms of plant cellulose involve rayon and cellulose acetate fiber. Rayon is still the most popular area of industrial scale use today, whereas cellulose acetate fiber is used in fabrics such as satins, brocades, jutes and taffetas. Cotton, linen, ramie, and hemp are the other examples of materials that are used to manufacture plant cellulose-based fabrics (Hearle 2001). These fabrics can be produced through two ways: Knitted or woven. Different types of knitted or woven patterns enable designers to give fabric the desired form by utilizing the material's elasticity in different directions. Besides, elasticity, the thickness also allows for various applications (Burnip and Thomas 1969).

### *Dynamic relaxation analysis*

Dynamic relaxation analysis is one of the convenient numerical methods for nonlinear structural analysis. The basics of this method involve adding an imaginary inertia, constraining forces to the static equation, and converting it to a dynamic system. (Rezaiee-Pajand and Mohammadi-Khatami 2019).

Antoni Gaudi's initial studies on the form of Sagrada Familia can be a great example to the use of dynamic relaxation analysis. He utilized the catenary geometries to form self-standing hanging structures, and inspired from them through a mirror underneath his hanging models. Colonia Güell is his another structure where the geometries are tension-only structures at first, but once they are reversed they can cope with the gravity and loads, and they can be transformed into a compression-only structures. According to many sources, Gaudi thought that the optimum form for arches or vaults are these catenary geometries that can carry their self-loads against gravity (Huerta 2006).

In this regard, bacterial cellulose-based tissue in a catenary form and its behavior was simulated in Rhinoceros 3D/Grasshopper/Kangaroo, a parametric structural analysis interface. In the digital environment, simulated bacterial cellulose and plant cellulose integration was performed and support positions were determined for a minimum deviation in the physical modeling of the tissue. Afterwards, bacterial cellulose and plant cellulose composite was transferred from the digital to physical medium. Bacterial cellulose and bacterial cellulose composite, which was analyzed in digital environment, was then tested mechanically against push-pull forces.

Kangaroo plug-in, a physics engine for an interactive simulation, utilizing the methodology of finite element analysis in the background, allows form finding and structural solving of tectonic systems. It provides a real-time & feedback-based process regarding each individual structural components. Kangaroo plug-in can be operated together with Galapagos plug-in, which is to find the optimum geometric fitness for the two undefined values of rotation and dis-

tance. It also provides a real-time feedback process while manipulating the components by possessing a high level of accuracy. Through a series of value inputs with number sliders, a variation of individual components can be created in relation with Kangaroo solver. In this Kangaroo solver, the locations of intersections of compressive rods, and tensile components such as cables or struts allow us to connect individual components within a continuous structural system. By this process, equilibrium for the overall system can be achieved (Piker, 2013).

In the regard of this research, first, an initial catenary geometry (Fig.1) is designed to investigate the mesh topology for the fabrication process in terms of the efficiency of spatial configuration and size/number ratio of the overall geometry.

The final form is tested through dynamic relaxation analysis to estimate the physical mechanical behaviour (Fig.2). This analysis was conducted using Kangaroo plug-in and Galapagos optimization plug-in for Grasshopper/Rhinoceros 3D which delivered a linear elastic analysis of the structure.

The inputs needed for the optimization process are the material properties, thickness of the structure, possible loads and constraints. The material is chosen as fabric, with 0.5mm diameter, loads include approximate dead load of native fibres (1.2 gr) and live load of bacterial cellulose (4.2 gr). The overall geometry fits into a 10x10cm boundary. When the simulation starts, the interface demonstrates the deflection, tensile stress lines and bending moment (Fig.3).

In the previous step, digital form finding and dynamic relaxation method is introduced and applied to a the geometry, however, the integration of digital form finding to digital fabrication holds great challenges for the realization of such discrete funicular structures. Since the membrane-like material is the bacterial cellulose, which is an alive matter, there are multiple considerations such as the optimum temperature, humidity, pH and environmental conditions.

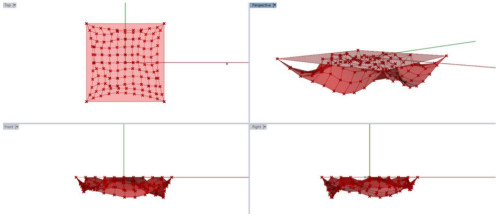

Figure 1
Initial catenary geometry

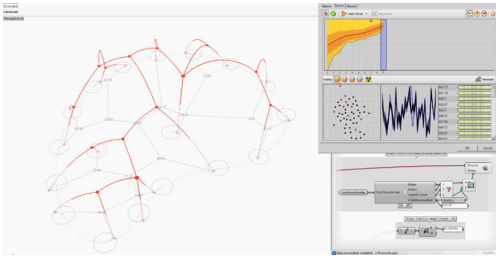

Figure 2
Dynamic relaxation of the catenary geometry

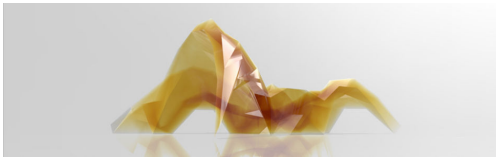

Figure 3
Resulting geometry from the analysis

In order to control the fabrication process of the geometry, direct information transfer from digital to physical realm is realized in two major steps. First, after the optimization process, final geometry is printed. Later, native fibres were positioned and bacterial cellulose tissue was laid as a membrane on the fibre network. Then, the 3D printed geometry is removed from the overall system, and the catenary structure is reversed upside down. After 3 days of adhesion process under room temperature (Fig.4), it is observed that the composite cellulosic tissue structure becomes solid and rigid to carry dead and live loads, while at the same time flexible at certain level. It is seen that the structure can carry 270 times its own weight (Fig.5). Moreover, it is observed that it remembers its original shape after it is deformed.

Figure 4
Composite cellulosic tissue structure

Figure 5
Compression test

## CONCLUSION AND DISCUSSION

The findings show that the dynamic relaxation simulation and compression test have both differences and similarities. While the deflection, tensile stress lines and bending moment were defined at the simulation, it was seen that the compression test has also resulted with the same deformations on the overall form. On the other hand, while the simulation was far preciser in terms of mathematical accuracy, compression test only provides evidences based on observations. In overall, the implementation of the transition from digital dynamic relaxation systems to behavioral systems was successfully conducted.

At the beginning of the research, cellulosic scaffold was expected to distribute the total load occurring from the tensile, compressive and other forces. Based on the digital data regarding the location of anchor points, the amount of dead and live loads and deflections on the structures were able to be identified. As the result, it was observed that the sample composite tissue structure can carry up to 270 times their own weight. In addition to its structural strength, the tissue have a certain level of elasticity which enable it to remember its original shape after it is deformed.

In the case of this research, the use of catenary structure for such a material that is relatively new to the structural use has proven effective as a design prototype because of its ability to self-stand and at the same time, to biodegrade. This kind of fabrication process has also proved that such processes can allow us to have accurate complex forms in a relatively short time for environmentally friendly products. Although the use of bacterial cellulose is still in its infancy as a part of the structural system, it still allows for further prototypes to explore more systems, e.g. maintaining the growth of the material instead of stopping the growth or scaling down and scaling up the end product, that respond to new sets of parameters in future.

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# D1.T1.S3. DESIGN AND COMPUTATION OF URBAN AND LOCAL SYSTEMS – XS to XL

# Post-Conflict Reconstruction

## *Small scale elements of a parametric urban design approach*

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*Taking the Syrian city of Homs as its point of departure, this paper aims to suggest some first components of a parametric urban design approach to post-conflict reconstruction focused on scenario building. From analyses of social, physical and environmental infrastructures and theoretical positions on environmentally and socially sustainable urban design in the Middle Eastern culture and climate, a framework and some initial tests for a parametric 3D urban model developed in CityEngine are presented. With the intended purpose of providing a tool capable of visualising modifiable urban design scenarios along with relevant associated data, the presented work focuses on the smallest scale of a model encompassing scales from the district level to the level of the urban block, with some relevant architectural features relating to social and environmental qualities.*

**Keywords:** *parametric urban design, post-conflict reconstruction, scenario building, climate-adaptive design*

In the past decade, destruction of cities and urban environments due to armed conflict in the Middle East has sadly brought the topic of post-conflict reconstruction (PCR) on the urban design agenda. Academic response to this urban destruction has focused mainly on historical urban cores and the loss of architectural heritage. But as most Middle Eastern cities have experienced rapid urban growth during the last half century, most of the damage has happened in contemporary urban environments.

In a context of weak - if any - urban planning, these environments already lacked a lot in terms of urban qualities. And claims have even been made, that the very nature of their urban morphology has contributed to building the stress and tensions that led to their destruction (Al-Sabouni, 2016). Rather than aiming for urban reconstruction as was, reconstruction efforts should therefore take the demise as an opportunity for the improvement of urban space.

Reconstructing urban environments with the aim of improvement relative to the pre-conflict situation is a complex endeavour. It involves not only planning, architectural and urban design issues, but also issues of power, economy and politics. Rather than working from experts' proposals and grand reconstruction masterplans, such attempts must therefore adopt a strategy of scenario building and communicative design (Steinø, Dabaieh & Ben Bih, 2020).

### *Homs*

The city of Homs is the third largest city in Syria after Damascus and Aleppo. It had an estimated pop-

ulation of around 800.000 inhabitants at the beginning of the civil war (Wikipedia). This number has declined dramatically due to extensive fightings causing hundreds of thousands of civilians to flee the city. The city including the historical centre consisted predominantly of contemporary concrete buildings with a typical height of eight storeys (Fig. 1).

Figure 1
Level of destruction in some of the contemporary areas in Homs. Source: www.unusualtraveler.com

As in many Middle Eastern urban areas, the city had developed as a twin city with formally planned middle and upper class areas predominantly for the historical resident population, and large informal lower class areas predominantly for poor rural migrants who have settled in more recent time.

The war damage is so extensive that large parts of the city has been almost completely destroyed (Fig. 1). Rather than an urban reconstruction aswas, this tabula rasa situation potentially allows for fundamentally new approaches to urban reconstruction. Given the many problems of the pre-war city, such as social segregation and urban spaces which do not respond to cultural and environmental needs (Al-Sabouni, 2016), this seems appropriate. The open question, however, is how this can be done.

### *Existing Plans and Proposals*

In 2015, a very generic 'general organizational plan' for the South-Eastern neighborhood of Baba Amr (Fig. 2) was approved by the Homs City Council. This 'copy/paste' plan features a deadpan street grid, filled with free-standing towers for offices or housing. While devoid of any architectural quality, it is organized along a central artery with a very large, open, ornamental plaza half-way. Essentially, however, this plan is completely indifferent to the socio-economic, cultural and climatic contexts of the locale, and akin to ever so many large urban schemes as they have been developed from China to the Arab region in recent decades.

As a critical response to this plan, local architect Marwa Al-Sabouni, known for har criticism of contemporary architecture and urbanism in Syria and its claimed role in the Syrian civil war, as expressed in her widely acclaimed book The Battle for Home: The Memoir of a Syrian Architect (2016), has presented a counter-proposal (Fig. 3), based on ideas put forward in her book. While Al-Sabouni's plan is equally bland and repetitive at the large scale, it does try to articulate a more adapted architectural space on the building/urban block level.

Figure 2
Aerial perspective render of the 2015 'general organizational plan' for the South-Eastern neighborhood of Baba Amr, Homs. Source: www.homsgovernorate.org.sy

### *Culturally and Environmentally Responsive Design*

Traditionally, Arabic Islamic cities have developed as morphological unities where the separation of urban planning, urban design and architecture is essentially meaningless. In response to climatic and cultural conditions, Arabic cities featured introvert buildings organized around inner courtyards (riads)

and with few, if any, openings toward the exterior other than the entrance door. These buildings were lining a hierarchical system of narrow alleyways, minimizing exposure of vertical surfaces to solar heating and providing horizontal shaft effects for wind cooling through the use of partly covered streets, bay windows and cantilevered upper storeys (Hakim, 1986).

Figure 3
Street level perspective render of Al-Sabouni's counter-proposal for Baba Amr, Homs. Source: www.archdaily.com

While traditional Arabic Islamic cities are generally 1-2 storey developments, contemporary urban development in the middle East is far higher with buildings from 6-16 storeys. Hence, many areas of Homs are developed with 8 storey buildings. While the principles of the traditional Islamic city are meaningful, this calls for a different morphological approach.

The responsiveness of urban design to environmental factors spells out at different scales in hot arid climates. On the urban scale, the natural landscape and topography impact natural and passive cooling due to factors such as convection, solar orientation and waterways (Pahl-Weber et al., 2013). The alignment of the urban grid to prevailing winds may also contribute to passive cooling (Visser et al., 2013a). Distributed, small green spaces reduce the risk of building heat islands and improve local and pedestrian access. While an non-hierarchical street network of broad and directly connected streets promotes vehicular traffic, a hierarchical street network with broad and straight connecting streets and more narrow and wiggly local streets promotes a differentiation of modes of transportation from vehicular to pedestrian (Pahl-Weber et al., 2013).

On the neighbourhood scale, providing shade and natural cooling in urban space is essential in order to create a comfortable environment. While narrow streets provide shade, trees provide cooling through evaporation (ibid.). Pedestrian-centered rather than car-centered urban space design promotes walking. In addition, comfortable access for pedestrians to mass transportation stops promotes access to more remote destinations by means of mass transit (Visser et al., 2013a).

Minimum energy consumption is a major sustainability concern at the building scale and may be achieved through passive and natural cooling and ventilation. Surface to volume ratio, opening percentage and shading devices impact the energy performance of buildings. Courtyards and openings may provide stack effect and cross ventilation, and thermal zoning distributes uses according to their sensitivity to heat (Visser et al., 2013b). Built back to back or along narrow streets, buildings may shade each other, and housing units may shade each other through stacking (Ben-Hamouche, 2008; Visser et al., 2013b). Integrating building designs with trees and green spaces increases thermal comfort through shading and cooling (Visser et al., 2013b).

## DESIGN APPROACH

While traditional Islamic building code meticulously negotiated adjacencies in the three-dimensional structure of the traditional Arabic city (Hakim, 1986), the contemporary capitalist mode of production has fostered an approach of minimal interference in urban planning, which is typically reached through separation of uses and spaces. The resulting urban fabric is one of voids and disconnection, both of which are unfortunate when it comes to producing a dense urban fabric similar to that of the traditional Arabic city.

In this design-based study, the termite mound has been used as a design metaphor to negotiate this challenge, as well as to respond morphologi-

cally to the considerably higher density of contemporary urban development in the Middle East. Termite mounds are ingenious structures built by termites to negotiate hot climate conditions. A fundamental principle of termite mounds is to organise an interior space as a system of hollows, linked by channels which facilitate natural ventilation, among other things. As such, termite mounds are to some extent similar to sponges, although with a higher solid/void ratio and with more variation of the structure across space.

Conceptually, thus, buildings are conceived of as 3-dimensional masses with voids. While functionally some voids may be circulation spaces - either horizontally or vertically - other spaces may be private open spaces. At the same time, spaces are interconnected spatially to constitute a system for ventilation through stack effects and natural lighting with minimum exposure to direct sunlight through extensive use of setbacks and building parts spanning over open spaces. Depending on the size and location of these structures, they may span across streets or sit between them.

## *Method*

Rather than trying to achieve an optimum design through computational optimization algorithms, this study is design-based. Thus, the study is based methodologically on form-making, rather than form-finding. This means that the design relies on experience-based, architectural knowledge, rather than engineering knowledge. Based on the design principles of culturally and environmentally responsive design as discussed in the previous section, the design concept has been developed using the morphological principle of the termite mound as a design metaphor, rather than as a literal principle. In order to test the design concept against measurable criteria, UTCI temperature has been simulated using Rhino/Ladybug.

The design concept consists of a hollowed out volume, which has been conceived geometrically as delimited by four exterior vertical surfaces in the form of (punched) facades, and any number of interior facades (Fig. 4). The external horizontal surfaces consist of roofs and roof terraces, while interior horizontal surfaces may be circulation spaces or private open spaces (courtyards). As any such volume is connected to neighbouring volumes and the rest of the city at the ground level, this allows the structure to be

Figure 4
Front elevation and long section showing exterior and interior facades

organised vertically as a hierarchical system of more local/private spaces in the upper storeys and more public spaces towards the ground level. In principle, this is similar to the (horizontal) hierarchy of the traditional Arabic Islamic city (Hakim, 1986). Following from this, vertically, interior spaces may hold retail and service spaces in the lower parts, and office and housing spaces in the middle and higher parts.

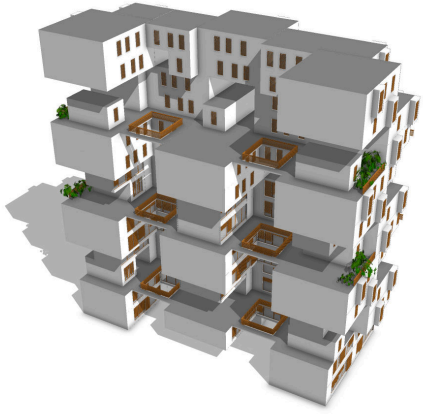

Figure 5
Perspective section showing internal open spaces, vertical shafts and horizontal voids

This far, the design does not rely on computation per se. However, as the aim is to design a volume which can be adapted to different lot sizes and dimensions, and building heights, the distribution of solids and voids inside the volume must follow a particular parametric principle. The principle adopted by this approach is one of a regular grid of vertical shafts or light wells (y axis, as CityEngine uses a y-up coordinate system) which may be connected to horizontally organized voids (x and z axis) which may connect vertical voids (shafts) to one another and to the exterior surface of the volume (Fig. 5). This logic is repetitive and thus expandible, as well as variable, as horizontally organized voids may differ in number and location across floors, depending on the requirements for solids - i.e. larger continuous spaces for office uses and more open spaces connected to housing.

Hence, the volume is organised as a three-dimensional matrix of solids and voids, represented by their location (index) along the x,y and z axes. This allows for the mathematical expression of difference within the volume by referencing the indexes, such as, for instance:

- If y < a, landuse = service/retail, if y < b, landuse = office, else, landuse = housing (assigning landuse by floor from bottom to top)
- If both x and z are divisible by 2, cell = void (producing shafts along the y axis)
- If z = zMax and face is oriented to the front, face = front oriented facade (selecting front facing exterior facades)

This logic allows for a very efficient production of the overall volume, in principle like a Rubik's cube with any number of cells along each dimension. This volume may subsequently be modified through series of mathematical queries in order to produce any desired local variations such as voids (vertical and horizontal), setbacks and facades.

If the overall void is considered as consisting of four sides, a bottom, a top and an interior core, the script may be coded such as to allow for the core to grow three-dimensionally and all other aspects to grow two-dimensionally from increases in plot size and building height, thus allowing it to adapt parametrically to any (four-sided) site condition matching some minimum requirements.

As mathematical queries may be used to produce any conceivable geometric modification, the approach allows for a large degree of flexibility and variation. This all the more so, as cell dimensions may vary along any of the three axes, as demonstrated in the example below.

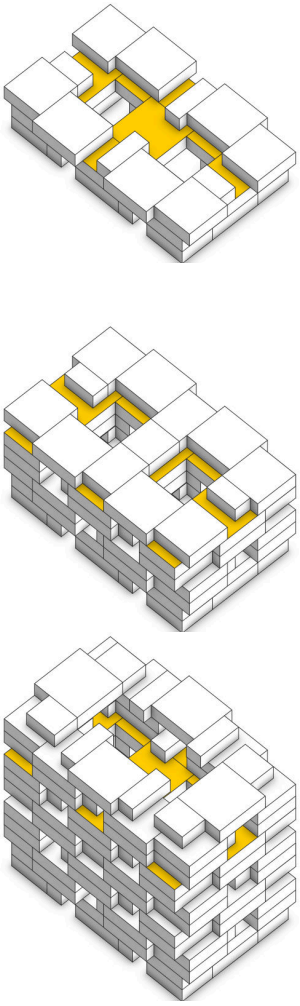

Figure 6
Diagrammatic isometric view with sections at a) level 3, b) level 7, and c) level 13, showing horizontally organized voids connecting to the vertical voids and to the exterior surface of the volume

## RESULTS

Results are presented with respect to the architectural quality of the building, its environmental performance, and its scalability and adaptability to different contexts. The architectural and environmental aspects have been exemplified in a simple 5 x 14 x 3 matrix (x,y,z) example for a building volume with two shafts and fourteen floors (Fig. 5). Floor plans for the building interiors have not been detailed. Floor plans may vary by application of the design concept and do not impact the environmental performance, nor the quality of outdoor spaces which are the focus of this study.

### *Architectural Qualities*

The aim of the design has been to design a mixed use prototype with four floors of retail and service in a sort of mini-mall structure with voids for circulation at the base, followed by 6 floors of potentially office space at the middle of the building, and an additional four floors of housing at the top. As the idea is that interior open spaces may, in part, constitute public spaces, this continues the principle of the Arabic-Islamic of a hierarchic distribution of urban space from public (souks, main alleys) to private (residential quarters, side alleys).

In order to produce outdoor public space on two levels (0 and 2) at the base, several horizontally organized voids have been made in order to connect to the vertical voids and to the exterior surface of the volume (Fig. 6a). At the middle of the building, on levels 4-9, less horizontal voids have been made, in order to allow for larger, continuous floors for office use. Here, voids are separated from one another in order to produce more secluded open spaces (Fig. 6b). At the top of the volume, on levels 10-14, several horizontal voids have been made in order to allow for more semi-public circulation space and private open spaces for housing (Fig. 6c).

Figure 7
Exterior view perspective rendering set in the context of dense urban development and streetscape with trees

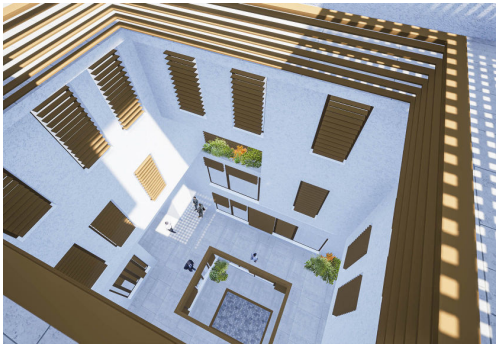

Figure 8
Perspective view through vertical shaft from top to bottom

Figure 9
Perspective view of internal void in the housing area at 10th floor

Architecturally, floors have been organized two by two in order to break down the scale of the 14 storey building. This has been accentuated through a system of setbacks essentially producing a vertical 'checkerboard' of alternating setbacks which leave the impression of stacked two-storey volumes. This adds the benefit of producing multiple shadows on the facades, which, in turn, potentially allows for reduced heating from solar radiation (Fig. 7).

Internal exterior spaces offer a shaded outdoor environment which is visually connected through the vertical shafts (Fig. 8). At the middle levels, large continuous floors provide floor areas suited to office use. Here, open spaces are more secluded and provide air and daylight into the structure. At the upper levels, the structure is more open in order to provide spaces suitable for housing. In a system of semi-private and private open spaces, penthouse-like apartments with roof terraces cluster over several floors to provide a small neighborhood in the sky (Fig. 9).

The exterior facades have been differentiated with respect to their location, At the base, the facades have more transparent and inviting facades with large shop type windows. Setback facades have smaller, regular windows, while protruding parts of the facade have regular windows and bay windows. Bay windows are alternating left to right in order to produce a harmonious rhythm across the entire facade. At the bottom floors, facades are flush, in order to accentuate the base of the building and make it compatible with a linear sidewalk space. Contrasting the base, the top floors form a penthouse-like situation with additional setbacks, in order to accentuate the top and create roof terraces.

### *Environmental Performance*

The building has been designed to accommodate shading through staggered facades, setbacks and voids, and brise soleils, and cooling through the stack effect of air through horizontal voids and rising up through the vertical interior shafts (Fig. 10). The cooling and shading concept of the building's open

spaces is developed from traditional Middle Eastern approaches to passive climate control. In principle, the stack effect drives heating air up through the central vertical voids causing air to pass in through horizontal voids at different levels of the facade. Air is cooled in part from shading trees at the ground level, and in part through vaporization from passing over water pools and through plants located at the horizontal voids. Shading from setbacks, cantilevers and protruding facade elements, as well as from plants, louvers and lattices reduces the direct solar load on the exterior of the building.

Figure 10
Section diagram showing inward and upward air flow in interior voids as a result of the stack effect

In order to have a first quantitative indication of the passive cooling effect of the structure, a temperature simulation based on the universal thermal climate index (UTCI) has been made using Rhino/Ladybug. The configuration mention at the opening of the Results section was used in a setting with trees surrounding the base of the building as shown in figure 7. Simulations were made for horizontal surfaces of level 0, 2, 6 and 10 (Fig. 11). The UTCI temperature simulations indicate that the outdoor temperature in the interior open spaces may be up to 5 degrees celcius lower, compare to surfaces in unbuilt open spaces, as indicated by the yellow color compare to the red color in figure 11.

It is noteworthy however, that only shading was factored in. If thermal mass and water were also factored in, it is likely that the temperature would lead to a result at least two degrees lower. Still this would not account for the cooling factor of moving air as a result of the shaft effect. This could be simulated using computational fluid dynamics (CFD) and might lead to even lower results.

### *Scalability and Adaptability*

Due to the parametric principles underlying the design, it can be scaled to fit different plot sizes and floor numbers (Fig. 12). It may span several neighboring plots - even across streets, as it may allow streets to pass through at the ground level. The relative distribution of different uses - shops and services, offices and housing - may vary according to local needs, as the system of internal open spaces may also vary by their number and location. Facades may vary with respect to the number and distribution of windows and voids, and the depth of setbacks and bay windows.

If applied systematically in continuous urban areas, the structure in combination with tree-strewn streets may offer a completely changed and radically improved public open space, compare to much contemporary Middle Eastern urban development, not only in streets but also in the interior of buildings. With maximum natural shading, cooling and daylight, this public space is potentially more visually and thermally pleasant and invite people to increasingly use public space by foot.

## CONCLUSION

The presented work describes a partial step towards an approach to post-conflict reconstruction in hot arid climate aiming to produce a 3-dimensional urban fabric drawing from the principles of the traditional Arabic Islamic city, yet adapted to contemporary densities through the application of a vertical hierarchy of open public and semi-public spaces inside building structures. Hence, traditional elements such as protruding and arching elements ('sabats') have been interpreted both at the exterior facades and in the internal voids in order to create shade while allowing for circulation in open spaces both at the base and at the top of the building.

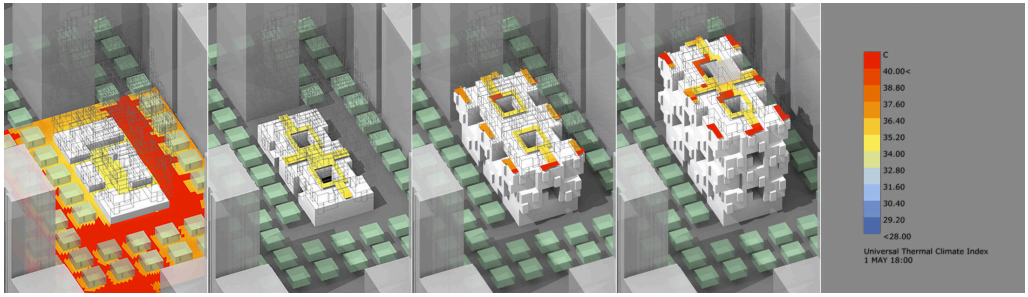


Figure 11
UTCI temperature simulations at level 0, 2, 6 and 10

The resulting architectural space offers the possibility of both a hierarchical distribution of land uses from public to private along the vertical axis, public and semi-public open spaces in the interior voids of the volume, vertical shafts allowing for vertical convection of air through stack effect, as well as architectural detailing and plants and water basins providing passive shading and cooling. UTCI simulations indicate that the design may provide an interior outdoor environment with temperatures up to 5 degrees celsius lower than for unbuilt open spaces.

Due to the parametric quality of the organisation scheme, the concept is scalable to different site conditions and building heights. The application example of the scheme shows its versatility with regard to the variation of the distribution of voids and the accentuation of the building through setbacks and facade variations. The organising device for this is the attribution of x, y and z indexes which allows for series of mathematical queries for the modification of individual cells within a simple, rectangular volume.

## PERSPECTIVES

In order to further test and develop the versatility of the organisation scheme, additional examples should be made for an array of different site and

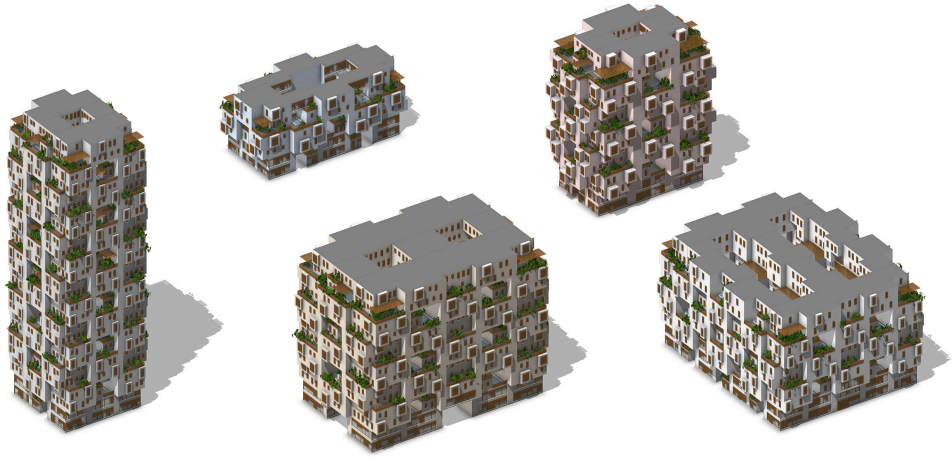

Figure 12
Parametric variations to the design featuring variations of footprint size and dimensions, number of floors and various facade variations

height conditions. Also different organisational principles for the internal vertical and horizontal voids, as well as for the architectural articulation of facades should be explored. At a more detailed level, different principles for vertical access through exterior and interior stairs and elevators should be explored.

In order to further test the environmental performance of the building, thermal mass and water were should be factored in for more accurate UTCI temperature simulations. Computational fluid dynamics (CFD) simulations should be made in order to analyse the stack effect of air rising through interior shafts.

## ACKNOWLEDGEMENTS

The author would like to thank assist. prof. Mads Dines Petersen, VIA University College, Horsens, DK, for his assistance on UTCI temperature simulations in Rhino/Ladybug; MSc. Eng. Kristian Mortensen for his assistance on plan, section and elevation drawings and diagrams; and BSc. Eng. Sarah Lassen for her assistance on perspective renderings.

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# Applying Deep Learning and Databases for Energy-efficient Architectural Design


## Abstract

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*The reduction of energy consumption of buildings requires consideration in early design phases. However, modelling and computation time required for dynamic energy simulations makes them inappropriate in the early phases. This paper presents a performance prediction approach for these phases that is embedded in a multi-level-of-development modelling approach. First, parametric pre-trained modular deep learning components are embedded in the building elements. The energy performance is predicted by composing these components. Second, embodied energy assessment is performed by extracting the information from a database. A calculation module queries the database and calculates the embodied energy. Both, embodied and operational, energy are assembled to predict lifecycle energy demand. The method has been implemented prototypically in a digital modelling environment Revit. A case study serves to demonstrate the application process, the user interaction and the information flows. It shows energy prediction in early design phases to enhance the environmental performance of the building.*



**Keywords:** *BIM, Operational Energy, Embodied Energy, Life-cycle Energy Demand, Early Design Phases*


## INTRODUCTION

The reduction of embodied and operational energy consumption of buildings requires consideration in early design phases because decisions made in these phases have a high effect on the performance improvement with limited costs of changes. However, simulation and calculation methods are not appropriate for making informed decisions in these phases. The information demand and the modelling effort are too high. Computation time, especially for multiple variants, is too long to integrate a dynamic simulation approach into early design phases. This paper presents a performance prediction approach for these phases that is embedded in a multi-level-of-

development modelling approach. First, parametric pre-trained modular machine-learning models are embedded in the building components (Geyer and Singaravel, 2018; Geyer, Singh and Singaravel, 2018). By composing the components, the dynamic operational energy performance is predicted without a detailed physical simulation model. The ML components are trained before the design process utilising parametric dynamic energy simulation which captures the thermal behaviour of the building design and its components. Second, for embedded energy, the information about components is enriched by using a database containing lifecycle-based embodied energy demand data for early design phases. A calculation module queries the applicable data and calculates the embodied energy. Both, embodied and operational, energy are assembled to result in total life cycle energy demand.

Design-embedded sensitivity analysis serves to determine parameter influence on energy performance and allows for the prioritisation of decisions (Harter et al., 2020; Singh and Geyer, 2020). The methods have been implemented prototypically and are shown in the digital modelling environment Revit. A realised design case serves to demonstrate the application process, the user interaction and the information flows. This demonstration includes screenshots of the implemented software, its application on the case and the results displayed to the designer. The case study shows how the component-based modelling approach embedding energy performance prediction can be applied to inform architectural design in early design phases to enhance the environmental performance of the resulting building.

## RESEARCH BACKGROUND

An early phase of design involves the development of a building envelope, which affects the environmental performance of the building significantly. A carefully designed building envelope has the potential to enhance environmental performance with a lesser cost of investment (Hemsath and Alagheband Bandhoseini, 2015). There have been several works to predict the environmental performance of buildings at an early phase of design. The challenges involved in predicting environmental performance, that have been addressed by other researchers, are summarised below:

1. Integration of digital modelling environment and energy prediction - A designer develops the building design in a digital modelling environment such as Revit, while an energy simulation tool requires building energy models (BEM). Thus, several researchers have developed a method to extract information from a modelling environment to develop BEM (Ahn et al., 2014; Negendahl and Nielsen, 2015).
2. Sampling to address inherent uncertainty in the design parameters - The early phases of design are characterised by inherent uncertainty in the design parameters (Tian et al., 2018). This uncertainty is addressed by simulating several energy models developed using a random sampling approach (Van Gelder, Janssen and Roels, 2014).
3. Operational energy prediction using the ML approach - It is a time-consuming process to run dynamic energy simulations on several energy models developed using a sampling approach. This challenge is addressed by developing data-driven ML models. ML models provide slightly less accurate results but make energy prediction significantly faster.
4. Lifecycle energy assessment - Most of the research works focus on either operational or embodied energy; thus the trade-off is not considered which exists between these two types of energy consumption (Dixit, 2017; Harter et al., 2020).
5. Comparison of design variants under uncertainty - There are only a few studies which put emphasis on the aspects of comparing design variants under uncertainty. A comparison of design variants under uncertainty is performed using statistical analysis (Singh and Geyer, 2019).

The previous research works address these challenges separately. An integrated approach is lacking which addresses all these challenges. It requires a BIM integrated quick environmental prediction tool which takes care of uncertainty and allows a designer to compare several design variants.

## RESEARCH METHODOLOGY

We are performing energy calculations at early design phases which is characterised by an inherent uncertainty in the design parameters. This uncertainty causes uncertainty in the energy prediction, which needs be dealt with by probabilistic energy prediction. We generate a number of samples using uncertain design parameters, followed by the generation of a number of energy models. These models are evaluated separately for operational energy and embedded energy predictions (Figure 1).

## OPERATIONAL ENERGY PREDICTION

Operational energy prediction is usually performed by performing dynamic energy simulations which require both modelling efforts and computational time. We have developed a data-driven approach using deep learning (DL) architecture and created machine learning (ML) based energy prediction models. We call this approach component-based machine learning model (CBML) for energy prediction. In this approach, a number of DL components are arranged in a hierarchical order similar to building elements arranged in building energy models (BEM). This approach also follows a typical hierarchical composition of elements in a BIM environment. First, DL components corresponding to each building element such as walls, windows, roof, ground floor, and infiltration predict the heat flow through them, followed by calculating zone level energy requirements such as heating, cooling and lighting and finally building level total energy consumption for one year. The readers are welcome to refer to previous publications on the development of ML-based operational energy prediction models (Geyer, Singh and Singaravel, 2018; Singaravel, Suykens and Geyer, 2018; Singh, Singaravel and Geyer, 2019).

These DL components are able to predict the operational energy demand for a large number of energy models within a few seconds with quite a high level of accuracy. The ML model, used in this paper, shows an accuracy of 0.998 (R2) and 3.08 (mean absolute percentage error, MAPE) on random building shapes, for the climate of Munich and building use as an office. Adaptation to other climate is possible as shown by (Singaravel, Geyer and Suykens, 2017); other type of use seems also to cause no problems. The prediction accuracy of the ML model is presented using the scatter plot in Figure 2. We used EnergyPlus simulation to generate the data for training and testing the ML model. Once trained, the models quickly predict the operational energy demand for any building shape; thus, they are suitable to be used for an early design phase.

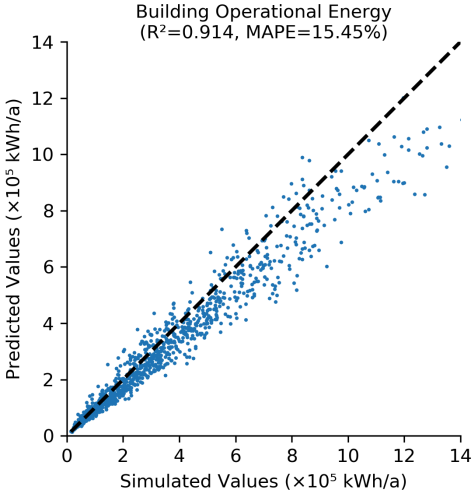



Figure 2
Prediction accuracy of used ML model

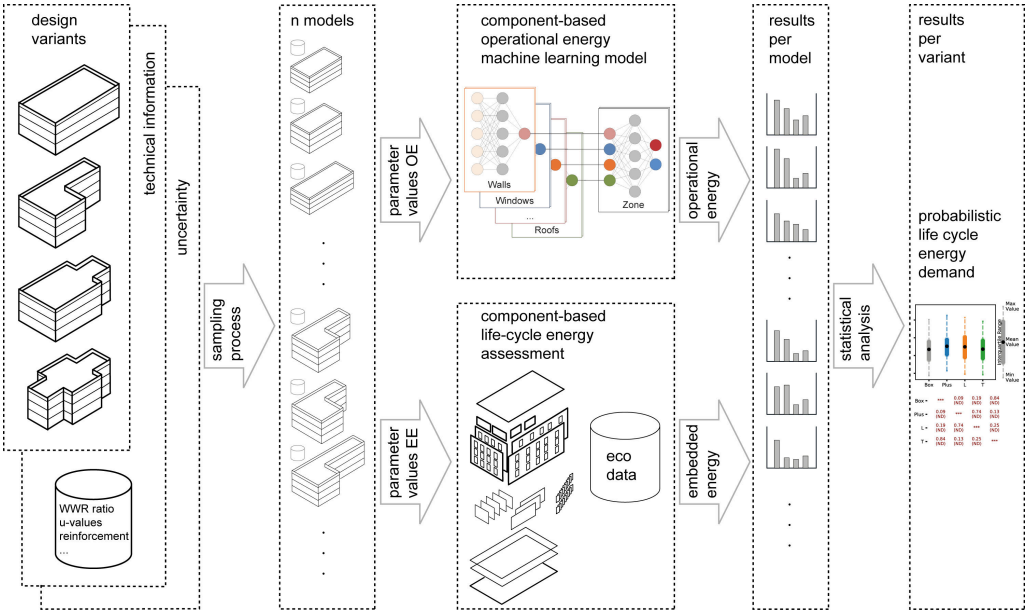



Figure 1
Calculation methodology

## CALCULATION METHOD FOR EMBODIED ENERGY

Embodied energy calculations rely on a life cycle inventory (LCI) and life cycle impact assessment (LCIA). The first step of the LCI for the sample building is the bill of materials. In our case, as very little information about the building is available in early design phases, we extract geometrical information from the BIM model, containing areas of various main parts of the building, namely exterior walls (opaque), exterior walls (transparent), interior walls, the base plate(s), floor plate(s), and roof(s). This information is enhanced by technical information from consulting engineers, e.g. u-values from the energy consultant or reinforcement percentages from the structural engineer. All design information is subject to uncertainties, which are estimated by the respective source of information (architects, engineers). Based on this information, the sampling process explores the model uncertainty resulting in a large number of parameter combinations each representing a unique building model. This sampling takes place in parallel to the sampling process for operational energy (OE) such that the set of building models for embedded energy (EE) matches the set of building models for OE. On the basis of the Oekobaudat database [1], we developed an early design phase database containing the main building parts mentioned above. This database is used for both the second step of the LCI - the database contains primary energy (PE) values for each building part - as well as the LCIA - e.g. environmental impact data, such as global warming potential (GWP). A calculation module assembles the primary energy values for non-renewable (PENRT) and renewable (PERT) primary energy per life cycle phase of the building and per building model. For a detailed description of the calculations, please refer to (Schneider-Marin et al., 2020).

## MERGING OPERATIONAL AND EMBODIED ENERGY

The results from the set of building models are merged using primary energy information obtained from Oekobaudat for the operational energy. PENRT and PERT values are added for each building sample to total PE demand values.

## TESTCASE

The basis for our test case is a real-life office building, the FTmehrHaus of Ferdinand Tausendpfund GmbH, built in 2017. The building is a rectangular 3-storey building containing approx. 1100 m$^2$ of offices, meeting rooms and reception. It also serves as a test case for the research project EarlyBIM (Abualdenien et al., 2020) of which the energy study presented here is a part of. We have generated three design variants to this rectangular shape (Box) building, as shown in Figure 3. These three design variants are named as L, Plus, and T based on the geometry of the floor plan. These are the common building shapes used in office designs (Harter et al., 2020; Singh and Geyer, 2020). We store these early design variants in a Revit environment to extract geometrical information without remodelling efforts for developing BEM.

## RESULTS

We conducted this study on the test case building, and the process and information exchange for LCEA is described in this section. The whole process of environmental performance prediction using the BIM integrated approach requires information to be exchanged among several tools, as shown in Figure 4.

In a typical scenario, the tool has 11 steps, as described below:

1. In the first step, the geometrical information about design variants is extracted from the BIM model.
2. In the second step, a user form is shown (as shown in Figure 5) to collect information about uncertain design parameters. The user enters the mean value for each design parameter and required variation. The user also defines the number of random samples.

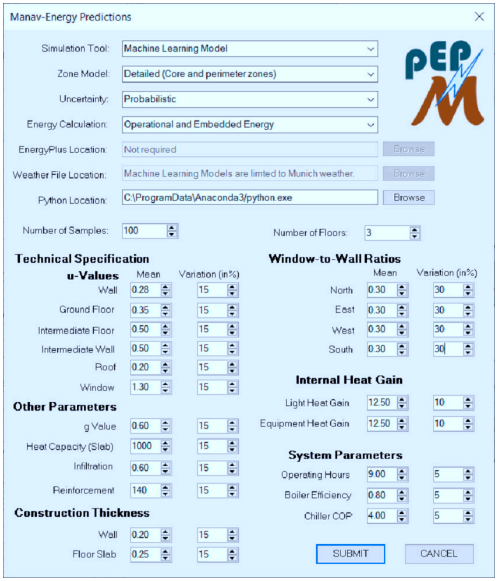



Figure 5
User-input form for collecting uncertain information

1. In the third step, the tool generates information to develop geometrical components of BEM. This step generates zone information, point coordinates of the wall, floors and roof.
2. In the fourth step, the tool generates a required number of random samples based on the uncertain design parameters. Currently, the random samples follow a uniform distribution.
3. In the fifth step, the tool generates building energy models corresponding to random samples.
4. In the sixth step, the tool creates input files for machine learning-based operation energy prediction. This step is performed using Python programming language. The operational energy demand, along with the heat flows through building elements, is predicted in this step.
5. In the seventh step, embedded energy is calculated using the database.

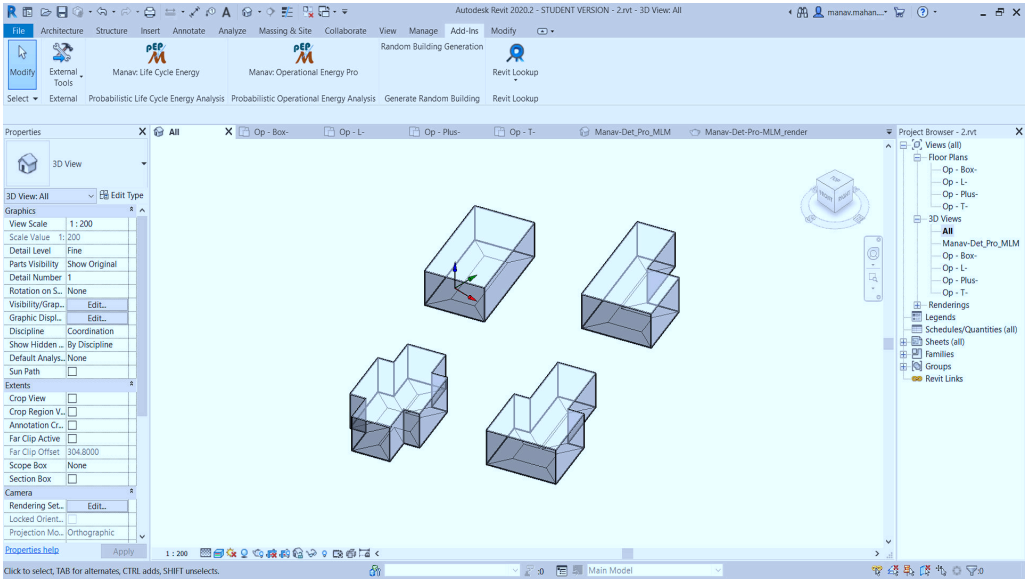


Figure 3
Different geometrical variants stored in Revit for energy analysis

1. In the eighth step, LCEA is calculated by combining the results from operational and embedded energy predictions.
2. In the ninth step, a statistical analysis is performed to compare the design variants. The analysis is performed using the nonparametric test - Wilcoxon rank-sum test. Wilcoxon rank-sum test is used to determine whether two independent samples selected from the population are significantly different from each other (Corder and Foreman, 2014).
3. In the tenth step, the LCEA results are associated with each building element.
4. In the eleventh step, the analysis results are integrated back in Revit environment for visualisation, as shown in Figure 6.

## COMPARISON OF DIFFERENT DESIGN VARIANTS

Using the developed tool, we compared four design variants, and the results are shown in Figure 7. We used 100 random samples for uncertain design parameters. It takes approximately 40 seconds to run the analysis. The building energy models are generated just in a second and the majority of the time is required to predict operational energy demand. It takes another 60 seconds to integrate the results, which is basically the generation of different elements in Revit environment.

We assume p-value of less than 0.05 to be statistically significant to conclude two variants are different from each other. The statistical analysis shows 'Box' variant is better than 'Plus' or 'L' variant as p-value is less than 0.05 and the mean value of energy demand is less for 'Box'. However, it is not possible to differentiate between 'Box' and 'T' as p-value is not less than 0.05. Similar criteria are used to compare other combinations of design variants.

Figure 4
Information exchange between the LCEA prediction tool

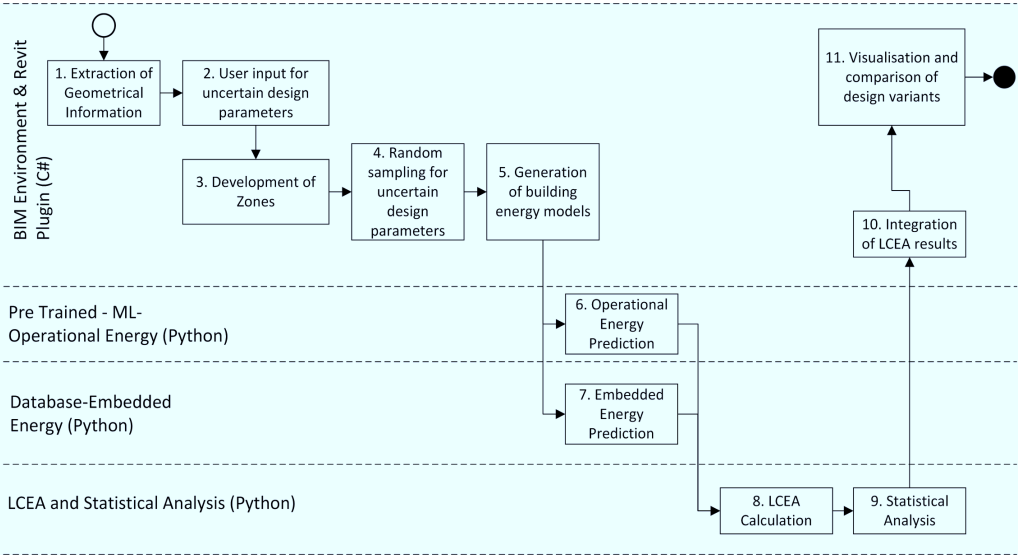
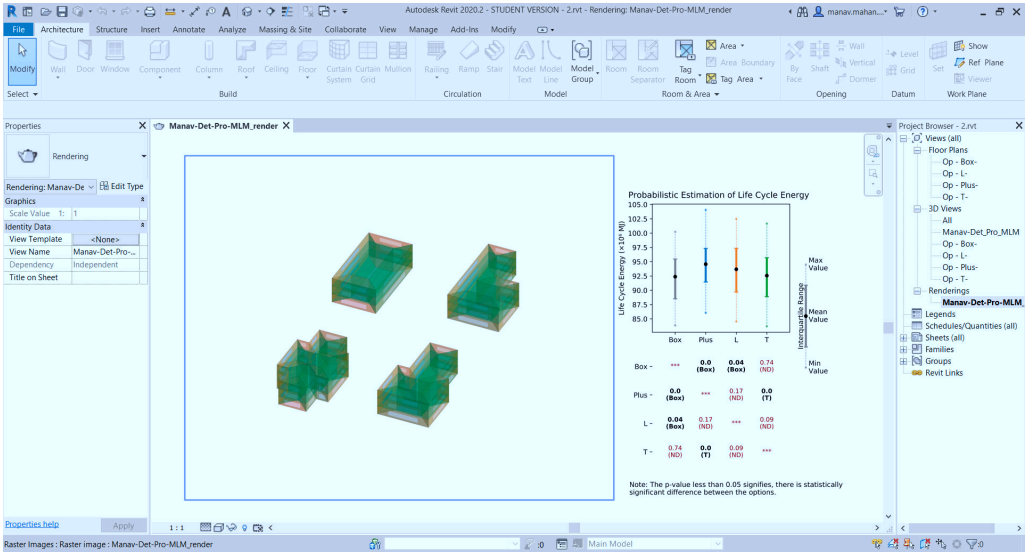



Figure 6
Visualisation of LCEA results in Revit environment



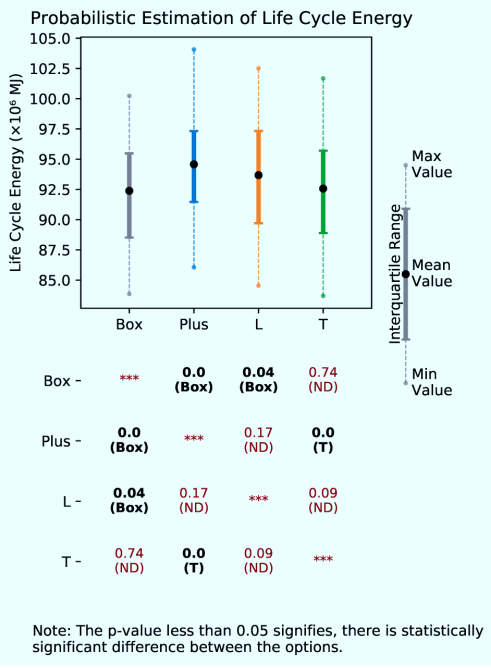



Figure 7
Comparison result for four design variants

## DISCUSSION

In this study, we have developed a collaborative approach to predict the environmental performance of a building in an early design phase. The developed approach is quick, considers uncertainty in the design parameters and compares several design variants using statistical analysis. The approach has two calculation modules, one for operational energy and another for embedded energy. The major limitations come from the assumptions of these calculations. The operational energy predictions are performed using ML models which are slightly less accurate than dynamic simulations, but exceptionally time efficient. Moreover, these ML models are applicable only to specific design cases. Such as in this case, the model works only for office buildings with the climate of Munich; however, it is not limited to such conditions. Similarly, the embedded energy calculation module works for Germany and it relies on only a few building materials. Hence, it does not take material uncertainty into account, which is the subject of future research. Similarly, the energy mix used to calculate the primary energy demand is case-specific, but it is possible to extend it for other energy mixes. Finally, we assume a uniform distribution of uncertain design parameters. However, this limitation can be overcome easily by introducing additional sampling schemes in the tool. We have tested the accuracy of the developed machine learning models on random building shapes which has rectilinear floor plans. However, the approach of machine learning models can be exteneded to more non-uniform building shapes as demonstrated by other researchers.

## CONCLUSIONS

The researchers have developed a BIM integrated approach to predict the energy performance of several design variants and compare them based on the performance. The developed approach has been demonstrated through a test case building. It has been shown that the proposed approach is able to predict the performance of several design variants quickly, suitable for an early phase of design. A random sampling approach and statistical analysis allow comparison of design alternatives under uncertainty.

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# A Tomographic computation of Spatial Dynamics

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*Waning of vigorous discourses about the idea of space as essence in architectural design concurred with the emergence of digital architecture. The notion of space was replaced with the underlying notion of form facilitating optimization of performances and form-generation in digital design ever since. Within the context of digital architecture, the current research investigates a formal method to reintroduce spatial aspects, based on dynamics of architectural space in relation to form, into digital design processes. Accordingly, a computational framework is devised employing the idea of space as dynamic field conditions, in order to capture dynamic interrelation of architectural space with architectural form. That is, spatial dynamics are regarded as data embedded in architectural space, that can imply operational aspects of spatial experiences and / or stimulate corporeal engagements with experiential space, as concepts as action potentials and affordances do (Rasmussen 1964). As a result, the research aims to contribute to the body of knowledge that endeavour to systematize architectural sensibilities that are implicit in design processes by externalization utilizing computation.*

**Keywords:** *spatial dynamics, dynamic field conditions, dynamic displacement*

## RESEARCH CONTEXTS

Since the 1890s when Adolf Hildebrand and August Schmarsow crystallized the idea of space as essential for the plastic arts, the notion of space viewed as being most fundamental to architecture persisted to Modernism (Ven 1987). In 1908, Hendrik Berlage postulated that "the aim of our creations is the art of space, the essence of architecture" and half a century later Louis Kahn added: "Architecture is the thoughtful making of spaces. The continual renewal of architecture comes from changing concepts of space".

Despite how fundamental it is to architecture, space is an intangible concept, thus vulnerable to be substituted by more tangible, quantifiable subjects. In 1993, the publication of *Folding in Architecture* edited by Greg Lynn (1993) marked the turn of the millennium, when the avant-garde that evolved out of it was regarded as "the quintessential architectural embodiment of the new digital technologies that were booming at that time" (Carpo 2004). As pointed out by Mario Carpo, the publication was a catalyst for a wave of changes caused by the emerging new field of digital architecture.

One of these changes within architectural discourse was a shift away from the notion of space towards the notion of form, also apparent in Lynn's own writing. Only a few years after the publication of *Folding in Architecture*, the notion of space becomes neutralized and replaced by the notion of vitalized form and its shaping forces in his subsequent publication

*Animate Form* (Lynn 1999). This transition is characterized by equating the multifarious dimensions of space with the underlying geometric description: "Traditionally, in architecture, the abstract space of design is conceived as an ideal neutral space of Cartesian coordinates" where "geometry provides the apparently universal language with which architecture assumes to speak through history, across culture, and over time". Such elevating of geometry and its resulting notion of form has abetted quests for form-generation practice driven by performance optimisation in digital design (Kolarevic and Malkawi 2005; Oxman and Oxman 2010).

## FIELD CONDITIONS IN ARCHITECTURE

Current shift in interest away from space towards form is not a new phenomenon but inherent to the history of the notion of space since its emergence in German aesthetics in the mid-19th century (Mallgrave and Ikonomou 1994). This is due to the fact that space and form are intricately interrelated. As the art theorist and perceptual psychologist Rudolf Arnheim describes it in his study on *The Dynamics of Architectural Form* (Arnheim 1977), "although space, once it is established, is experienced as an always present and self-sufficient given, the experience is generated only through the interrelation of objects. ... Space perception occurs only in the presence of perceivable things".

Human spatial perception, therefore, is inextricably intertwined with the presence of objects; according to Arnheim, the interrelation of form of these objects activates a spatial field that define spatial experience (Arnheim 1977). That is, the spatial dynamics can be seen as relational field condition as explicated by Stan Allen in *From Object to Field*: "Form matters, but not so much the forms of things as the forms between things" (Allen 1997). Such a perspective is analogous to Arnheim's emphasis on interstitial spaces in dynamics of architectural space (Arnheim 1977). Interspaces, as he continues, are filled with gradients whose density and intensity dynamically change according to the configurations of objects, not necessarily strictly bound to metric measurements of and amongst the objects in consideration. Objects interconnected across space activate dynamic forces that influence the density and intensity of spatial field. Consequentially, the dynamic whole displays the characteristics of a highly charged continuous field. Furthermore, multiple number of such field conditions could be incorporated to facilitate new organisations emerging at the moments of intensity within their continuity, since field conditions - even in planar configurations - are capable of revealing hidden values of the system when combined (Allen 1997). (Figure 1)

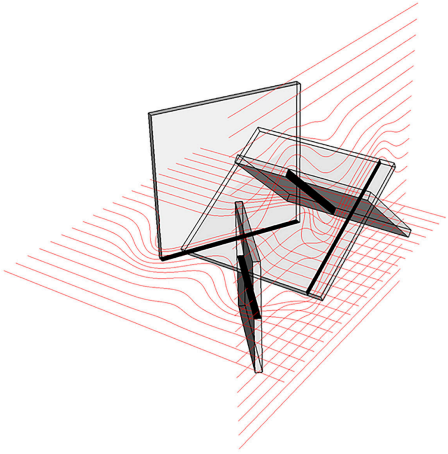


Figure 1
Dynamic field conditions are actuated by relations of objects in the spatial field. Multiple field conditions can be captured and systematically synthesised to reveal otherwise intangible spatial data.

'Field conditions' are quintessential peculiarities of complex dynamic systems. Dynamics in the spatial field become intelligible through emergent variations of density and intensity of the 'field conditions', induced by actuation of spatial field in relation to the objects within the field, rather than as any absolute numeric values; hence, emergent patterns by actuation of the field become 'carriers of information' regarding the dynamics of the spatial fields. Such is an understanding of field conditions familiar to conventional architectural practice where contour maps are used to convey topographic information. Densities of contours, thereby, are residues of geological forces

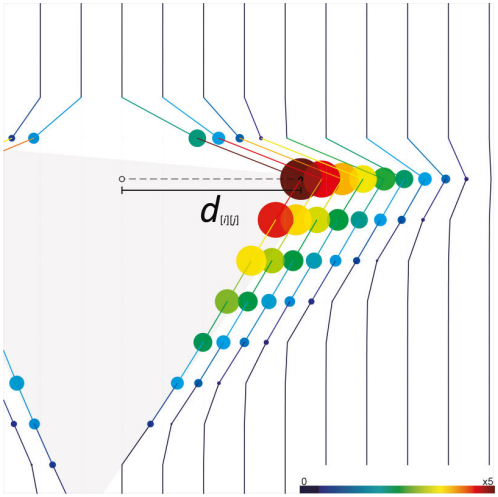
Figure 2
The dynamic displacement function is defined by measuring the deformation of the homogenised state caused by the objects within the spatial field. A color scale is used to visualise the range of values by the dynamic displacement functions.

in action - of the past or the present, or the prognostics of potential movements of objects (animate or inanimate) in the environment.

Referring to non-mainstream digital practices experimenting architectural potentials of digital technologies, digital tools that are currently utilized in architectural design can be tuned and sensitized to detect dynamic forces in the spatial fields activated by objects' relations. The curated digital sensitivity can also be steered to measure the resulting deformation induced by those forces, and to record patterns emerging in dynamic field conditions. Ultimately, the mappings of deformation of the spatial fields not only simulate and analyse complexity of spatial dynamics, but also can externalize spatial data to render them communicable.

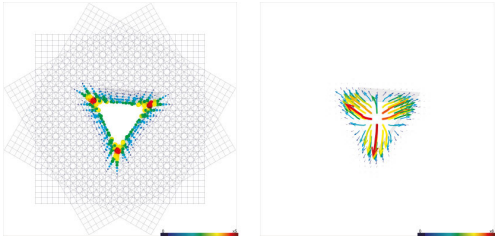
## TOMOGRAPHIC COMPUTATION OF DYNAMIC FIELD CONDITIONS

Following this conception, dynamics in the spatial field are activated by interrelations of the objects within the spatial field. In other words, the interrelations between objects actuate a neutral field and activates a differentiated field dynamics. Upon activation of the dynamics, the field conditions can manifest two distinct states; the neutral, homogenized state and the actuated, deformed state. Each state can be studied utilizing the tomography-like approach dissecting the spatial fields into multiple layers of spatial data to visualize sectional behaviours of the deformation of the spatial field. The visualization process of the deformations can be illustrated as dynamic displacement function (Figure 2). Within this paper the focus is on spatial phenomena within a single section of the multiple layers of data. The measuring of dynamic displacement functions is based upon single axis of the sectional plane at a time; that is, one operation of the dynamic displacement functions provide readings based upon one axis on the sectional plane. In other words, the definition of the dynamic displacement functions is dependent on the direction value of the axis on the section plane that they are set upon.




Therefore, in order to achieve a comprehensive reading of the deformations on the tomographic sectional plane, multiple measurements need to be acquired by rotation of the axis of the dynamic displacement functions. The computation of the functions encompassing the whole rotational range of the sectional plane can be assembled to constitute an integral mapping of the layer. Such process naturally means that the resulting assemblage of the dynamic displacement functions on the plane is dependent on the rotation resolution of the axis defined in each set of computation of the functions. The higher the rotation resolution of the measuring axis is, the more sensitive the computation towards the geometric particularities of the objects in the spatial field becomes, until increments in the values of its sensitivity stabilize (Figure 3).

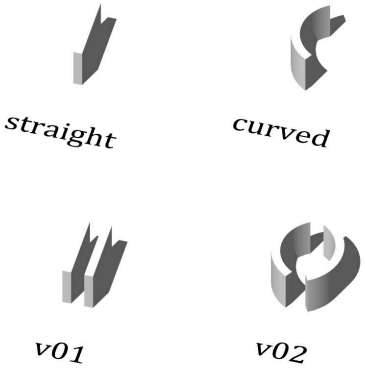
The resulting assemblage of dynamic displacement functions depicts behaviours of spatial dynamics on the section plane (the tomographic layer), the dynamics generated by the objects in spatial fields of continuity. The synthesized data of the tomographic layer can also be used to constitute a vector field of the spatial forces that are active on the sectional plane - presented as vector flows in the mapping.



These two sets of information, one regarding the dynamic displacement function and the other the vector flow, allow a reading of the spatial dynamics within the tomographic layer (Figure 3).

## TEST STUDIES USING SECTIONAL INFORMATION

To assess the computational framework, a series of test studies are devised using simple structures derived from architectural archetypes introduced by Thiis-Evensen. The cataloguing of archetypes in his study is based on the human corporeality and phenomenological experiences in relation to perceived space form in architecture (Thiis-Evensen 1989; Mallgrave 2018).




Two baseline cases are established consisting of single straight wall for one and single curved wall for the other, followed by variations with the same type of wall added to each baseline case (Figure 4).

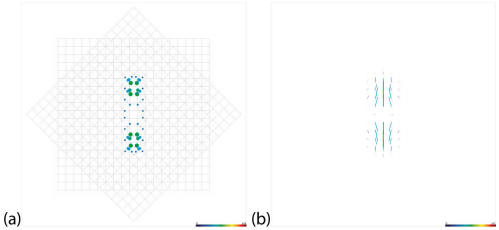
Primarily, the vicinity of the object is filled with multidirectional gradients of intensities and densities of spatial dynamics. The gradients progress from lower to higher values in intensity and density of the dynamics, not only towards the objects from farther away in the spatial field but also towards the ends of the walls from the middle (Figure 5). The ends of the walls highly charged with spatial forces can be observed in the mapping of the dynamic displacement functions by actuation of the spatial field, while they appear even more accentuated by the vector flow patterns indicating the attracting forces around (Figure 5). Accordingly, the mappings exhibit that the dynamic displacement function identifies points of special interest as high intensity points.

To discuss the resulting mappings in more detail, in the case of single curved wall (Figure 5b) is presented the condition of asymmetry in spatial dynamics, contrary to the symmetric behaviour of the case of the straight wall (Figure 5a); deformation patterns in the mapping of the dynamic displacement functions by actuated spatial field of the former exhibit differentiation between convex side and concave side of the wall. In addition, the comparison of the vector flow patterns of spatial dynamics in both cases illustrates that the former displays expanded gradients of dynamics with distinctive spatial forces that are active around the middle of the wall. That is to say, curved geometries can generate more diversified spatial dynamics compared to straight lines, since they are more intelligent and better informed, therefore can negotiate differences through continuity (Spuybroek 2004), while expanding the affected field area of basal behaviours engendered by straight geometries.

Figure 3
Overlaid multiple dynamic displacement functions produced by rotation of measuring axis on the sectional plane provide a holistic view of the deformation and, thus, of the field dynamics induced by the object in the spatial field (left). This information can be used to generate vector flows that materialise the movement of particles within the object towards the object boundaries (right).

Figure 4
Basic archetypical forms used in the exploration of spatial dynamics by comparative analyses.

Figure 5
Baseline cases of the test studies consist of the case of single straight wall (Top) and that of single curved wall (Bottom). Each case is presented with two data sets, actuation of the spatial field (Left) and vector flows of spatial forces (Right)



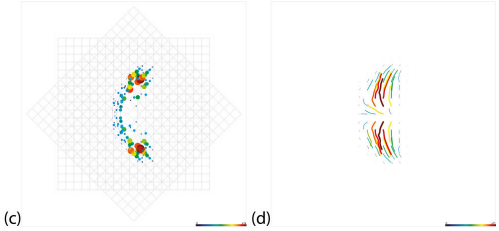
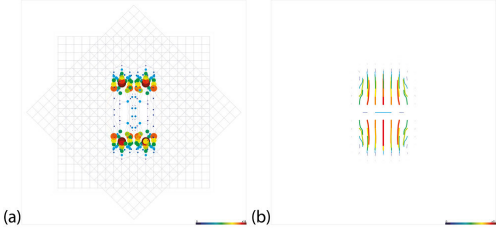
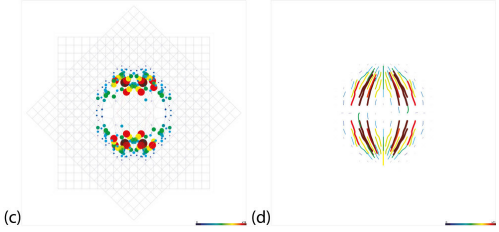




Figure 6
The variations are established based on the baseline cases. Addition of one more element can generate emergent behaviours of more interactions in spatial dynamics.




Each variation established by adding another element in the spatial field affirm latency of more interaction as it appears to amplify the behaviours of each baseline case, a large part of whose features is preserved (Figure 6). The results of the variations enable to speculate capacities of multiple geometries interacting in the spatial fields to generate complex spatial dynamics. Interactions of multiple objects in the spatial fields not only influence the behaviours of spatial dynamics in the interstitial space, but also those in and around each object. For example. The range of intensities of spatial dynamics over the whole spatial field for the single straight wall (Figure 5a and 5b) significantly expands when it interacts with another straight wall (Figure 6a and 6b). In addition, the latter visualizes stronger presence of spatial forces that are perpendicular to the length of the walls, as well as those that are in-between the two, compared to the former. The similar behavioural changes are observed in the case of curved walls. (Figure 6c and 6d) It could be assumed that the computation of spatial dynamics detects symmetries of each object and of the configuration of the objects within the spatial field, which could be explored further in future research.

## CONCLUSION

As presented, the research acknowledges that dynamics of architectural experiences - including designing as well as occupying and appreciating - are deeply associated not only with the human corporeality and sense perceptions the human body is capable of processing, but also with intrinsic interrelations of architectural space and architectural form. Therefore, architectural design as space creation cannot be disassociated from the underlying concept of spatial dynamics. As mainstream digital practices in architectural design are increasingly detached from such fundamental discourses despite assertions by precedent architectural theories or studies in the other fields such as neuroscience (Mallgrave 2018), it is imperative to address and incorporate spatial concepts into the current digital design practices.

The computational framework proposed in the paper is the first stage of such attempts. The initial sets of its application demonstrate that gradients in diversified intensities and densities of spatial dynamics operate as carriers of spatial information. Spatial information in architecture can be imbued with architectural intents - 'affordances' or 'action potentials' - that can convey utilization of the

space and / or evoke corporeal vitality stimulating the human sense perceptions (Rasmussen 1964; Gibson 1986; Massumi 2004; Mallgrave 2018). That is, continuity of dynamic field conditions is the aspect of space that can convey differentiated magnitudes of spatial information (architectural intents), while complex behaviours of spatial dynamics can be generated through geometric manoeuvres and topological relationship of geometries within spatial fields. Such design operations are usually undertaken by architectural sensibilities throughout design processes that are challenging to be explicitly communicated. Nevertheless, computational design research continuously endeavours to comprehend architectural sensibilities and explicate cognitive processes in design, so as to expand design knowledge while articulating it to be better communicated (Oxman 2006; Terzidis 2004). The current research aims to contribute to such endeavours and explore possibilities of architectural computation beyond the current efficiency-driven use of digital technologies.

With the formation and implementation of initial framework presented in the paper, more variations are to be tested with geometric, spatial and topological variables including curvatures, distances or symmetries. Moreover, further development of the tomographic computation method is to centre around synthesis of the spatial dynamics data, based on sequential relations of tomographic layers. The overarching goal of the research is to develop the tomographic computation to be operative for architectural design purposes, for analysis as well as synthesis of spatial configurations, while systematizing implicit spatial concepts through computation.

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# From Systems to Patterns and Back

## *Exploring the spatial potential of dynamic patterns in the area of regional planning*

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*The main goal of this paper is to present a decision support tool that translates systemic thinking and dynamic patterns into an immersive computational design method and through improved communication and simulation of abstract and complex urban data enhances the planning processes dialogue between different stakeholders and supports decision-making processes. The author presents a multi-level immersive and tangible interface setup consisting of technical and conceptual elements that, as a whole, through the use of dynamic patterns visualise the interaction of distinctive agents in the Finnish Lapland. It addresses the lack of a holistic approach and incorporation of dynamic patterns in the planning process by proposing a decision support tool that uses the results from these investigations to inform decision-making in planning and design tasks.*

**Keywords:** *System Thinking, Dynamic Patterns, Large-scale Planning Methods, Immersive Data-Interaction*

## INTRODUCTION

Public participation in decision-making processes is deeply rooted in Nordic countries (Nordregio, 2017). For example, Finland has been amongst the first countries to embed participation by law (Finland's Land Use and Building Act, 1999). However, the use of participatory methods is often not integrated on a meaningful level into the planning process.

When dealing with emerging planning challenges, planners and stakeholders are faced with raw-data packages that are often beyond human cognitive capacity to comprehend. Processing and discussing it effectively with stakeholders is challenging with traditional planning methods due to its complexity. Mapping, for example, does not have the dynamic and temporal aspects of the built environment and, thus, does not portray temporal correlations between different data-packages (Cantrell & Mekies, 2018). This often results in the reiteration of the same information without moving forward with the decision-making process.

Chris Leckie, a computer scientist, calls it a "high value" problem. He states that "[...] the access to the vast amount of data demands a high level of critical thinking, forcing to pick out the interesting or unusual events that are worth exploring and then filter them down to high-value problems" (Leckie, 2013).

The proposed approach incorporates the temporal aspect and dynamic patterns into spatial analysis and its representation, thereby overcoming this issue. It combines System Thinking, dynamic patterns, a simulation model and a tangible user interface.

### *The Arctic Region as a Case Study*

The Arctic region and the Arctic Ocean Railway have been chosen to act as a case study for the introduced research problem. It is a suitable example due to the emerging large-scale complex spatial transformations and power relation imbalance in the decision-making processes between local and global stakeholders (Clare, 2018). Because of these characteristics in similar projects across the region, it is likely that in the near future the Arctic region will need serious attention and new combinations of planning methods and tools to address it.

### *Systems Thinking & Dynamic Patterns*

Dynamic planning processes contain a high number of spatial narratives that emerge from the need to structure the built environment. Commonly, they are separated due to spatial complexity, thereby not covering the existing linkages and variety of shaping forces. This is especially so within the Arctic region where the actual boundaries and relations between these spatial narratives are strongly intertwined and complicated as they behave differently in relation to seasons in time.

Since Systems Thinking provides a standard method and domain-independent vocabulary (Batty, 2013) it can accommodate multiple different concepts and ideas. This allows filtering down spatial data and abstracting the Arctic region's narratives into patterns of interaction.

In the book "Dynamic patterns" (2017) Karen M'Closkey and Keith VanDerSys define patterns as "[...] relational frameworks that simultaneously describe and project; they reveal structures, processes, and relationships, as well as physical structure frameworks that give shape and form to our world", therefore "patterns - formal, material, or temporal recurrences - are essential for perception" (2017). However, the role and impact of these patterns on spatial transformations across the Arctic region are only studied on a general level and not yet used in decision-making processes.

The projects in this book highlight the relevance of suitable tools to observe dynamic patterns. Through the organisation of data, including relationships among different datasets, they can empower designers to curate the design process by developing greater insight into where they can have agency and impact (Wallis & Rahman, 2018). For example, displaying characteristics of on-going processes in the built environment that are not continuous in itself might help to overcome counterintuitive spatial assumptions.

### *Interaction & Computational methods*

In recent years Systems Thinking and dynamic patterns have gained new relevance due to current techniques enabled by computational methods and because they convey a dynamic aspect, while having the ability to manage large data packages within the built environment. This pairing of systemic thinking and computational methods is driven by the fact that both are topological by nature and focus not on form but rather interdependencies (Fricker et al., 2019). Combined with a tendency to use interactivity in planning processes it allows the possibility to manage attention while negotiating environmental and social conditions in planning decision-making.

Such a tendency originated from the Architecture Machine Group (AMG) led by Nicholas Negroponte in the 1970s. AMG, now the MIT Media Lab, continues to develop interactive interfaces that address the inability to deal with large-scale problems (Halper, 2019). A recent example of such interactive interfaces is the CityScope framework - a tangible user interface that is combined with simulation models and is used for civic engagement, urban development, and decision-making (Grignard et al., 2018). Hence, the increasing complexity in the planning tasks turns planners and designers toward developing interactive tools (Halper, 2019) that

integrate pattern-driven computational methods in the participatory process. While often the emerging data-driven planning and design methods are being misunderstood and considered a threat in traditional practices, it might support professionals as a logical advancement in design tasks (Fricker et al., 2007).

Simulation models are one example of a computational method that conveys the dynamic aspect of the built environment and which can integrate patterns. They are explored in practice and in academic work. For example, this approach is well articulated by Keith VanDerSys and the PEG office of landscape, which uses modelling to reveal changes in systems where patterns represent processes that have a physical impact (Cantrell & Mekies, 2018). Furthermore, a range of urban simulation tools have different levels of interaction. For instance, UrbanSim [1] SimTable [2], Relational Urbanism Models (RUM) [3] can be interacted with through tangible elements, browser or software interfaces.

The GAMA[4] simulation platform is a modelling and simulation development environment for building spatially explicit agent-based simulations (Taillandier et al., 2019). So far, it has applications in climate adaptation (Bhamidipati, 2015), planning transportation networks (Nguyen et al., 2012) and evacuation simulation (Macatulad & Blanco, 2014).

In this paper, the simulation model developed with GAMA is based on the pattern-oriented agent-based (POM-ABM) modelling approach (Grimm et al., 2005) and is utilised in a large-scale emerging planning task.

While Chapter 1 covers the strengths and limits of used methods, the following two chapters show the main contribution of the paper, in terms of introducing the new findings and designed methods. Chapter 2 presents the proposed workflow, that in an alternative way combines existing methods. Chapter 3 showcases the proposed workflow application.

## RESEARCH METHODS

The research methods follow a multi-method approach. Each chosen method is part of an interconnected workflow to create an interactive decision support tool. By bringing different aspects to the workflow, the selected methods reinforce each other (see figure 1).

### *Pattern translation steps*

*Step 1. Identifying agents across selected spatial narratives.*

Each spatial narrative contains agents that can be divided into three levels. Level 1 includes conceptual agents, like institutions, organisations or administrative mechanisms. Level 2 includes static physical agents, like railway tracks, mines, resorts or pasture areas. Level 3 represents dynamic agents, like moving trains, herds or passengers. Since the focus of this research lays on direct spatial conditions, Level 2 and Level 3 agents are further investigated.

During this stage, the relevant agents within the selected spatial narratives are identified.

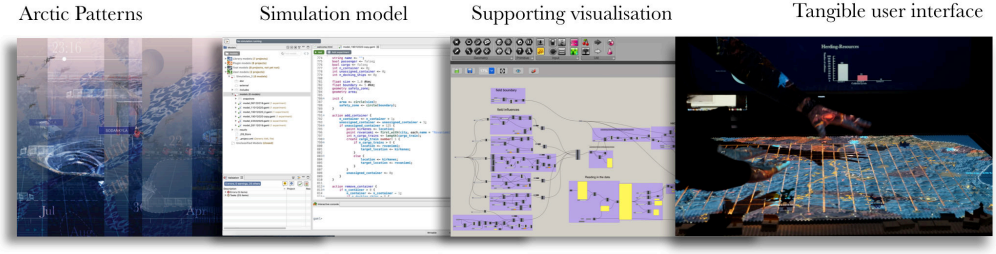



Figure 1
Diagram shows the integral parts of the proposed methodology.

*Step 2. Identifying common attributes across agents.*

The identified agents have attributes. It is a characteristic, common to one type of agent, but its value might be unique for different realisations of this agent. For example, agents might carry content, have a direction or reoccur over time. An accurate depiction of these attributes may be done by experts which have the critical knowledge to define it.

During this step, common attributes across different agents are identified and characterised.

*Step 3. Investigating which datasets are available to present the attributes.*

The defined agents' attributes have static or dynamic values that usually come in the form of datasets. Often, several types of sources need to be factored in, such as schedules, timetables, charts, feasibility studies or reports. The use of some datasets, like excel sheets, CSV files or GIS layers is straightforward, while reports or feasibility studies need to be generated in a suitable format.

During this step, available datasets are explored, collected and processed.

*Step 4. Defining the agent behaviour.*

The correlation and interaction between attribute values shape the agent's behaviour and its relations to other agents.

During this step, groups of experts might be involved to support linking agent behaviours with specific attribute values, conditions or rules.

*Step 5. Designing the simulation model.*

This part of the research concentrates on the design of the simulation model. Realistic agent behaviour is achieved by implementing the agent's attributes through employing corresponding datasets for values, rules and conditions for an interaction. In such a way, the descriptive information about the agent is translated into its computational parameters.

When running the model it simulates realistic behaviour within a site-specific modelled environment.

*Step 6. Validation of implemented patterns through readable outputs.*

The model is designed to provide the users with different dynamic output layers, like a collision map, a collision counter, direction vector maps and an agent's effort counter. Since simulated dynamic patterns in the model are a digital representation of real-world patterns, the output layers visualise it in a readable format.

The below presented outputs are examples that fit and support the chosen case study. However, since they are a generic visualisation of interacting patterns, outputs can be used in other cases as well.

*Collision map.* This allows the possibility to distinguish moments where and when different agents collide, based on a set of predefined rules for interaction. This output displays occurring collision distributions over time in the modelled environment (see figure 3a).

Immediate or accumulated collision maps can be displayed by choosing different time intervals, e.g. for a cycle, hour, day or a month.

*Collision counter*. This supporting display visualises collisions between different agent pairs on three levels - conceptual, static and dynamic. It potentially informs about the impact of different agent species on each other (see figure 3b).

*Direction vector map*. Static agents have a direction as one of its attributes. When combined with direction vectors of topographic elements they can form a vector field. The generated vector field displays the underlying path-like directional structure (see figure 3c). The observed path-like structure, emerging due to the collision of different vector directions, constitutes areas where impacts of the vector field sources are weakest and could potentially work as least impactful routes for all types of agents. Such a strategy is used for e.g. road network planning, as it could make the transportation network more inclusive.

This output allows observing directional organisation in the region that, as a result, can inform, for instance, road network structure or static agent distribution.

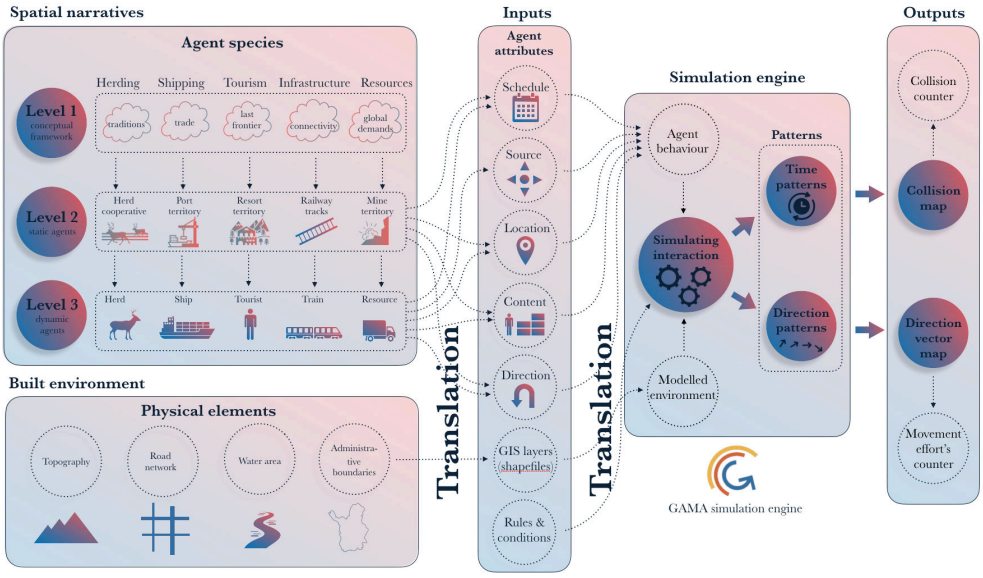



Figure 2
Diagram showing the model structure: 1) Agent species of selected narratives. 2) Input: agent attributes, built environment datasets, defined rules and conditions. 3) Inner model processes that simulate agent behaviour and interaction. 4) Output layers: collision map, direction vector map, supporting displays - collision counter and movement effort counter.

*The movement's effort counter*. This supporting display visualises the effort required from dynamic agents when moving across the vector field. It shows the agent's path and its movement effort along it. The effort value is calculated by comparing vector field values and dynamic agent's direction vector values (see figure 3d).

### *Involving stakeholders - A new trajectory for digital participatory methods*

In such regions as the Arctic, where there are large physical and conceptual distances, it becomes challenging to incorporate stakeholders in planning projects, read complex data and to find suitable means to interact with it.

An example of a framework bridging stakeholders and complex urban data is the CityScope tangible user interface. It is developed by the MIT Media Lab CityScience group researchers as an ongoing research theme (Hadhrawi & Larson, 2016). The framework aims to visualise complex urban data, to simulate the impact of real-time interventions, to support decision-making in a dynamic, iterative and evidence-based process and to innovatively address the demand for proper collaborations and public engagement (Alonso et al., 2018). These features make it a suitable framework for this research.

The CityScope setup consists of three layers. The computational layer is the simulation model, the physical table with LEGO(C) works as a tangible layer, and the communication between the former two via a scanner is the interactive layer. The scanner is built using a generic web camera and Python code available at https://github.com/CityScope/CS_CityScoPy. Such coupling of tangible objects with projected information from the simulation model allows for a very close mapping between the physicality of an object and the abstraction of visualisation (Schneider et al., 2011).

Current examples of CityScope applications mainly covers city-block scale (Alonso et al., 2018) and city scale (Noyman et al., 2017). Facilitating this

setup in a regional scale explores the framework's potential in large-scale planning tasks.

## FINNISH LAPLAND AND THE ARCTIC OCEAN RAILWAY PROJECT

In recent years, the Arctic region has received more attention, driven primarily by the re-emergence of the Northern Sea Route and the growing international trade driven by the rise of Asian economies (Brady, 2017). There is also the accelerating trends of nature-based tourism and increasing global demand for raw minerals (Similä & Jokinen, 2018), all of which reshape the livelihoods of local indigenous populations (Stephen, 2018).

One of the projects in the Arctic region drawing attention is the Arctic Ocean Railway [5]. It is an ethically, technically and economically challenging infrastructure development. The railway crosses national borders, multiple environmentally and culturally sensitive areas in Finnish Lapland, involving local and global stakeholders that have different incentives and concerns (Finnish Transport Agency, 2018).

On the one hand, the project sounds like a natural expansion of the regional mobility network, providing global and national benefits e.g. strengthens resource transportation and a shipping route alternative in the Arctic or improving mobility networks in the upper Lapland for tourists and the local population (Finnish Transport Agency, 2018).

On the other hand, it neglects the indigenous people's role in project development and would potentially create serious implications on herding patterns and could accelerate land fragmentation (Murdoch-Gibson, 2018).

The discussion about the Arctic Ocean Railway was initiated already in 2012. After multiple feasibility reports (Finnish Transport Agency, 2018; Norconsult, 2018) in 2019 it was concluded that the railway was not feasible at the current stage. However, a new local situation, like the opening of a new mine, could change it. With current planning tools, such situation-changing scenarios are difficult to explore.

The used strategies to assess this project with mainly descriptive reports do not convey the dynamic and temporal aspects of the project, thereby limiting the way stakeholders can perceive and manage it.

Therefore, the spatial analysis methodology needs to include and evaluate the multiple relations of the Arctic Ocean Railway project with different fields and stakeholders. This gap is addressed by applying the presented research method for this case study (see figure 2).

The introduced CityScope tangible user interface (TUI) is combined with the designed simulation model outputs (see figure 3) and additional displays that, as a whole, represents a decision support tool for planning and urban design tasks, named CityScope Lapland (see figure 4).

While the generic CityScope code for the communication between the model and the in-built scanner is open-source, the case study required to design a unique simulation model and a set-up facilitating specific interaction with time and direction parameters to assess the case study.

The interaction between the LEGO(C) modules on the table and the simulation model is built for several agents species. It allows choosing shipping season months for ships across the Arctic Ocean, train frequency along the proposed railway route, reindeer herd migration dates, lifecycle stages for existing and potential mines and to test different flight trend scenarios in Finnish Lapland.

## DISCUSSION

In this paper we speculate that the manipulation of dynamic patterns in a simulation model broadens the representation of initial raw data and uncovers otherwise invisible patterns in complex planning challenges, such as the Arctic Ocean Railway case, which potentially could improve the decision-making process.

The outputs generated from the simulation model confirm this hypothesis, as they uncover patterns invisible through classic planning methods, e.g.

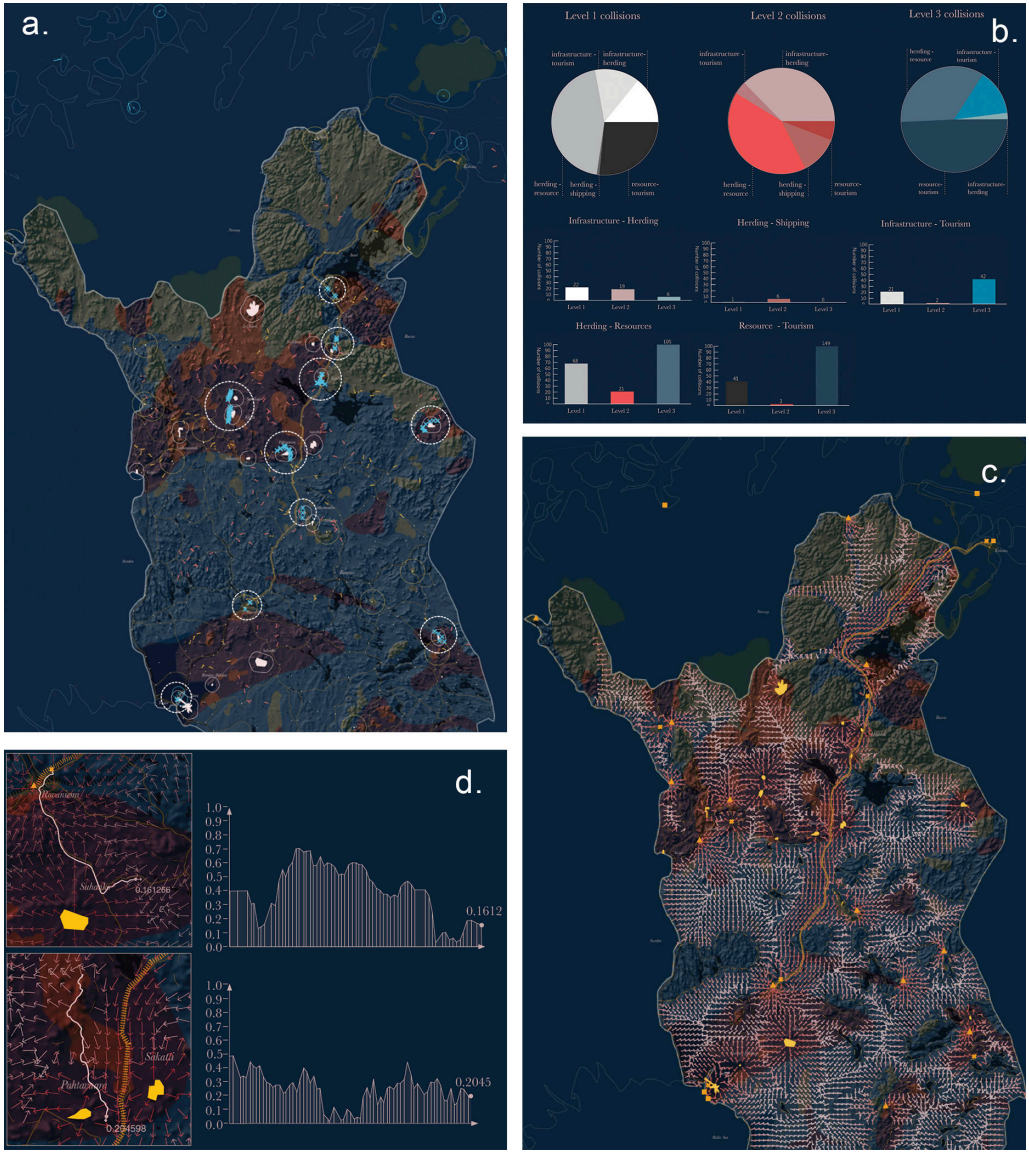



Figure 3
Snapshots from a running simulation model of generated dynamic outputs a. Collision map. Blue crosses present the locations of level 3 collisions in Finnish Lapland occurred over 5 days (04.20-04.25). b. Supporting collision counter display visualises the number of collisions and ratio between different agent pairs on three levels - conceptual, static and dynamic. c. Dynamic direction vector map shows the generated Lapland directional vector field with path-like structure, based on the level 2 agents' and topographical elements' direction vectors. d. Supporting movement effort counter displays the dynamic agent's path and movement effort values along it.

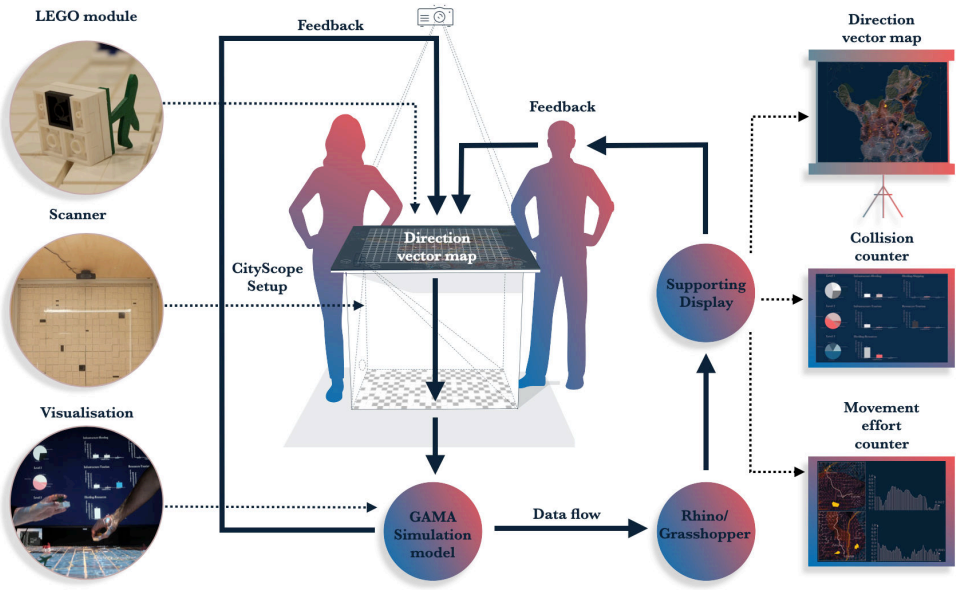



Figure 4
Diagram showing the different parts of the CityScope Lapland decision support tool: The feedback loops between different parts, the GAMA simulation model, the physical CityScope table and established communication between computational and tangible elements using a scanner. The additional displays show supporting outputs.

path-like structure in the direction vector map output (see figure 3c). It shows that geometric patterns can be generated through behavioural patterns, supporting Cantrell and Mekies idea that "reoccurring patterns in various phenomena can become the very material that shapes it" (2018).

The presented method in this paper has several strengths. Different outputs demonstrate possibilities of alternative data visualisations that move from descriptive to pattern-oriented data representation. It is an attempt to understand the Arctic system beyond two-dimensional representations, like mapping. Therefore, the use of dynamic patterns provides additional support to other planning methods due to the particular suitability for complex urban systems.

Since the model structure is modular and expandable, it has the ability to cut across scales and explore from single individual agent scenarios to regional-scale scenarios through reconfiguring (Halper, 2019).

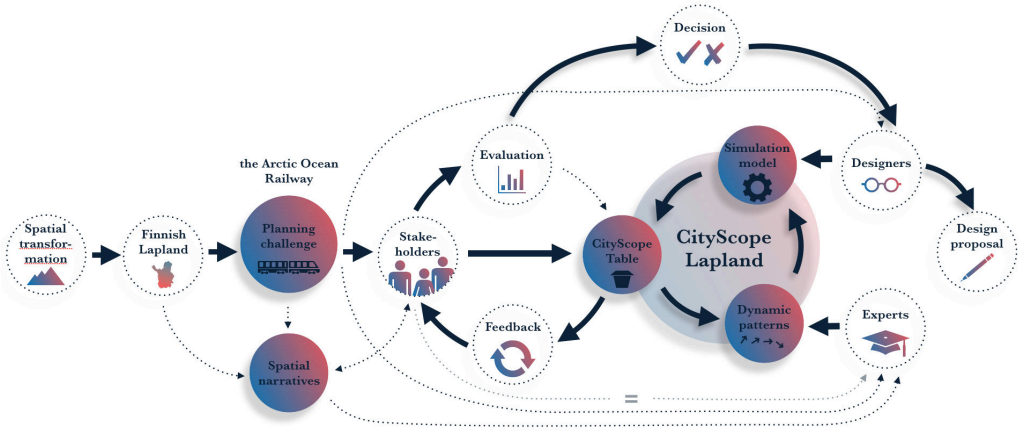
The tool expands a typical agent-based model workflow by including additional step - a tangible user interface - and brings non-expert stakeholders into the design and decision-making process as active participants.

Therefore, the presented workflow constitutes an alternative approach to planning, improving decisions by non-experts and supporting dialogue between the designers, the experts and the stakeholders (see figure 5). It renders planning processes more transparent and promotes accountability amongst all involved communities. As for planners and architects, it allows for easier trace back decisions that shape the boundaries of future design projects.

The proposed planning and design decision support tool also has some limitations in its current version. However, many of them are model-specific and could be solved with further development.

Readable representation of agents and their behaviours in the model is crucial. Therefore, suitable abstraction levels should be carefully selected. Fail-

Figure 5
Diagram shows the flow of the designed decision support tool CityScope Lapland used in planning and design tasks.




ure to do so can lead some stakeholders to reject the results altogether.

While modularity is essential, too many spatial narratives and agents potentially puts an upper limit on the time required to compute. However, it has to be fast enough to maintain a smooth flow of interaction and feedback (Batty, 2013).

Furthermore, the reliability of the simulation results is impacted by the input data quality. Building an accurate model requires the involvement of experts from different fields to decode chosen spatial narratives into specific patterns.

## CONCLUSIONS

The presented decision support tool translates Systems Thinking and Dynamic Patterns into a digitally-enabled computational design method. Through improved communication and simulation of abstract and complex spatial data, it offers alternative ways to perceive and measure spatial challenges, while enhancing the dialogue between different stakeholders.

Besides the simulation model, which can be integrated as a plug-in to simulate data interaction, the work contributes to remedy the ongoing challenges in participatory processes. The presented pattern-driven decision support tool can be integrated into the official planning process of cities and municipalities, connecting to the existing digital twin models of Helsinki for instance [6]. The integration process should include user studies, which would be a natural continuation of this work.

As for the Arctic Ocean Railway case study, the paper proposes a better-informed alternative strategy on how the project could be assessed using time and direction patterns of relevant agents.

## ACKNOWLEDGEMENTS

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[6] https://kartta.hel.fi/3d/#/

# The Evolutionary-algorithm-based Automation of the Initial Stage of Apartment Building Design

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*The development of information technologies has resulted in a strong return of interest in the concept of automating the design process. Most of the attempts such as works of Hersey and Freedman, Duarte or the PRISM application are based on shape grammars. Another approach is evolutionary simulations in concept creation augmentation such as works of Dogan, Saratsis and Reinhart or Nahara and Terzidis.This study examines to what extent evolutionary algorithms can be used to automate early stages of residential multi-family building architectural design. To facilitate informed decision-making, a tool capable of analysing a building plot and proposing the best fitting building shape was designed and tested with Polish legal regulations taken into consideration.A script generating, analysing, and evolutionally optimising a 3D model of the apartment building, was developed. All models met the basic legal conditions and were optimised by four criteria - view obstruction, insolation, maximal allowed floor area built and building compactness. The script was later used on selected building plots producing thousands of solutions. The best performing solutions were selected and presented together with their calculated parameters.*

**Keywords:** *genetic algorithm, evolutionary simulation, residential building, design automation*

## INTRODUCTION

To date, mass production has been dominating in many industries including architecture. Computer automation in design and construction allowed for mass customization. Even though not everything in architecture is quantifiable, not all relations are geometric and not everything can be combined into a system of dependencies (Meredith, 2008), the algorithmic design opened great opportunities.

The problem of computer automation of design (Mitchell, 1970; Alexander, 1967) and art (Stiny & Gips, 1971) has been worked on since the very beginning of the computer era and the interest in architectural design automation is growing in recent years (Duarte, 2005; Knecht & Koenig, 2010; Kwieciński & Pasternak, 2016; Dogan, Saratsis & Reinhart, 2015; Guo & Li, 2017; Hamacher & Kjølsrud, 2014) and [1].

One of the ways to automate architectural design is generative design, in which the designer does not directly manipulate geometric data, but only sets the rules by which the object is to be created (Larsen, 2012). The rules defined by the designer need to be

formalised and saved in digital form. Generative tools include, but are not limited to, cellular automata, L-systems, fractals, shape grammars, and genetic and evolutionary algorithms. The principle of the latter is inspired by processes occurring in nature, i.e. recombination and mutation of genes, i.e. the parameters of individuals that are improved from generation to generation. In nature, only the best-adapted individuals have the chance to pass on genes to subsequent generations, which means that each subsequent generation is increasingly better adapted to the conditions, and thus closer to the optimal solution. In architecture, genetic algorithm analyzes one or more optimization criteria at the same time and searches for the optimal solution in the process of negotiating its individual parameters (Rutkowski, 2012). The architect gives control over the entire process to the algorithm or limits the algorithm to only minor tasks, such as arranging windows to an already designed facade.

Generative algorithms can be employed in architecture design to a different extend. In general, design problems that can be described quantitatively and solved with some objective solutions are more likely to be parametrized and optimized than problems associated with aesthetics or meaning. Therefore an apartment buildings design seems to be an interesting field of parametric research, especially when it comes to preliminary design including site location and massing of an apartment block. At this stage a number of interconnected parameters of the new building, like the height, number of storeys, floor areas etc., has to be defined or calculated. Regardless their importance to the workflow of the individual architect, who may prefer to ignore the numbers and focus on the visual aspect of the creative process, these parameters have to be carefully controlled due to the clients requirements, building codes and zoning regulations. For these reasons, we believe that employing automation and optimisation in the process of apartment building preliminary design can be very productive, especially when compared to similar efforts undertaken in other architectural sectors where effectiveness plays less important role.

In this article we present a practical example of this approach: evolutionary optimization tool, which generates an apartment building's massing for a defined site. The tool, here under the provisional acronym MOT (Massing Optimization Tool), works with constraints of building code and zoning regulations and attempts to reconcile quality and efficiency of construction and maintenance of the building.

## METHODS

MOT supports the first stage of the architectural design process by automated generation of the optimal massing of the apartment building. In the optimisation process it takes into account the available floor area, compactness, insolation and view obstruction. All solutions meet the technical conditions set by the Polish building code and zoning regulations of the particular site. The algorithm was created for the hybrid man-machine workflow: to achieve the best architectural result, the designer can manipulate the system's input parameters and rules. MOT was developed in Rhinoceros, Grasshopper and Wallacei optimisation add-on [2] based on NSGA-II (Deb, Pratap & Agarwal, 2002).

MOT operates in six main stages:

### *Stage 1 - basic inputs*

Input data, specified by architect according to zoning regulations, specific demands and creative decisions, adopted by the algorithm in the first stage include:

- **Plot boundaries** - the outline of the area on which the building is to be generated, given as a planar closed polyline of any shape.
- **Building envelope perimeter** - a closed polyline inside which the entire building must be located. This parameter is also used to convey architect's intentions to MOT - for example protecting a selected part of the plot against building development or forcing a specific form of the building.
- **Applicable perimeter** - a fragment of the building envelope perimeter, on which the building

wall must be located.

- **Minimum and maximum building width** - a range of values expressed in meters in which the MOT can search for the optimal building width.
- **Building Coverage Ratio (BCR)** - ratio of the building footprint area to the plot area
- **Floor Area ratio (FAR)** - ratio of the total area of the building to the plot area.
- **Maximum building height** - value expressed in meters measured from the ground level to the top of the attic of the building.
- **Outlines and heights of buildings from the immediate surroundings** - closed polylines defining the outlines of neighboring buildings with their respective heights.

The algorithm with respect to other parameters, maximizes the total floor area of the building to the value determined in the zoning plan. In order to generate a massing of a volume lower than maximum permitted by regulations, the architect adjusts the intensity parameter manually. At this initial stage of the algorithm operation, the user may also decide to change other parameters resulting from local law in order to adapt the final result to his own expectations.

Figure 1
Graphic explanation of terms used in shape generation process.

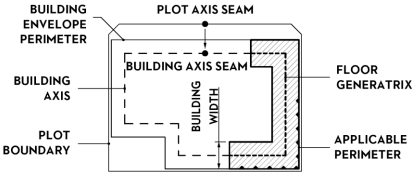
### *Stage 2 - the feedback loop*

In the second stage, the algorithm works in a feedback loop: basing on the input data, new parameters are calculated and presented to the designer. The plot geometry retrieves information about its area, which, in combination with the FAR parameter, determines the maximum total building area. The storey heights determined by the user in conjunction with the planning data allow to calculate the maximum number of storeys. The algorithm also suggests if lowering the storey height would allow for increasing their number. With this feedback the basic constraints defined in the stage 1 can be adjusted before going to stage 3.

### *Stage 3 - geometry generation*

In the third stage the algorithm chooses the gene values adopting the width and the length of the building for each floor separately. The number of storeys and location of the building on the plot as well as the position of each storey relative to the lower floors is also determined (see Figure 2). The final step of this part of the algorithm is the three-dimensional building model creation.

On the technical level, the building shape is derived from the building generatrix as a both-sides offset at a distance of half the width of the building. The building generatrix is a subcurve of curve offset by half the width of the building away from the building line. The length of the generatrix is the length of the entire building measured along its axis. (see Figure 1)




Each floor is based on a different generatrix that, if shorter than the floor beneath, can be additionally moved along the building line. A special case of such a shift is the movement of the ground floor determining the location of the entire building on the plot.

In each iteration, the algorithm determines what part of the total floor area will be realised by which floor, assuming that the upper floor is never larger than the floor below it and the ground floor area does not exceed the maximum BCR. The sizes of individual floors are then presented as the respective generatrix lengths. In the next step, the values of the parameters defining the building width and the floor shifts are chosen, each time assuming that the story (n + 1) does not go beyond the outline of the story below (n).

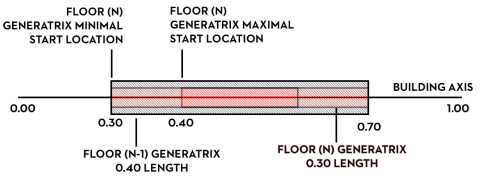



Figure 2
Floor plan outline shifting calculation diagram.

In the end, the 3D model of a building is generated by extruding the outlines of all storeys.

## STAGE 4 - EVALUATION

The 3D model is evaluated in the fourth stage. Genetic algorithms, including the NSGA-II algorithm incorporated in the Wallacei add-on evolutionary solver used in MOT, require fitness functions to assess the quality of the solutions. MOT evaluates each generated model according to the four numerical criteria described below.

**fitness function 1: compactness and footprint.** The first evaluation criterion, chosen because of the impact on the construction and operation costs, searches for maximum compactness and minimum building footprint. Both of these values describe similar building features, so the authors decided to combine them into one function. The compactness of the building is calculated as the quotient of the sum of the surface area of the building envelope and building footprint to its volume. This fitness function is minimized by the algorithm.

**fitness function 2: total area.** Although the algorithm by default generates buildings that use all permissible FAR, sometimes such solutions cannot be implemented due to exceeding the other parameters. For such cases the solutions with larger total area are assessed higher.

**fitness function 3: view obstruction.** Polish building code requires new buildings to meet the following maximal view obstruction condition in all living rooms and bedrooms:

*between the arms of the 60° angle, determined horizontally, with the apex located on the inner face of the wall on the axis of the window, there must be no obscuring part of the same building or other obscuring object at a distance shorter than the obstruction height - for obstructing objects lower than 35 m high*

It should be understood that a room complies with this regulation when it has at least one window in which a 60° angle (in which no part of the designed building or any existing building higher than the distance between the window and this obstacle is located) can be drafted. On the algorithm level, this condition is checked over the entire length of the facade in the interval specified by the user, as there are no apartments and windows designed yet. The longest string and the total number of "potential window spots" not fulfilling the view obstruction condition are treated as the third fitness function to be minimized by the algorithm. The position of the windows not fulfilling the condition can then be displayed by the user as additional information for subsequent interior design.

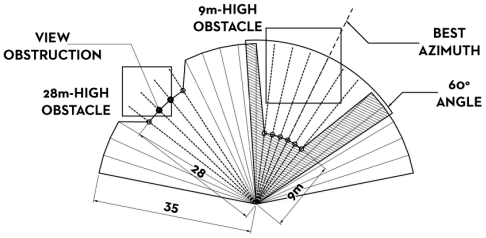



Figure 3
View obstruction calculation method.

**fitness function 4: insolation.** According to Polish building code, each multi-bedroom flat must have at least one window sunlit for at least 3 hours between 7-17 on equinox days. This condition is verified in evenly distributed points on the entire facade by checking whether rays derived from these points in accordance with the sun's vectors cross any existing or designed obstacles. For each point the number of rays not crossing any obstacle is calculated. The

algorithm maximizes the total insolation time of all sun exposure test points and minimizes the longest string of points not meeting the condition. Insolation of the facade can then be displayed on the model and serve as additional information for subsequent design.

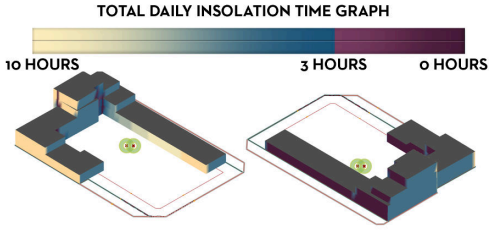



Figure 4
Total daily insolation time graph.

In addition to the fitness functions, the algorithm checks three boolean conditions: building placement next to the applicable building line, the distance between the most distant non-obstructed points and the distance between the most distant points that meet the insolation condition. Failure to comply with any of them results in rejection of the entire solution and the transition to generating the next one.

The third and the fourth stages are repeated in a loop. The generation size is defined by the user and the default value is 50 solutions per generation.

### *Stage 5 - optimization*

In the fifth stage the solutions of the current generation are randomly paired Next, the better performing solution's genes from each pair are crossed with the other analogue , creating an offspring. For example, the gene crossover in MOT's allows an offspring to inherit floor generatrix ratios from one of the solutions and building width from another one. Then the new population's genes are randomly mutated by 5% and all created offsprings are added to the current population. The better performing half of the generation population is selected using Pareto fronts according to nondominated-sorting and crowding distance comparison, basing on the results of four fitness functions (compactness and footprint, total area, view obstruction, insolation), and assigned as the new current population for further optimization. The number of generations is subject to modification, however, by default, the algorithm works for 100 generations.

### *Stage 6 - solution selection*

In sixth stage, all solutions are analysed and the best ones based on user-specified parameters are selected. The Author has expanded the analysis possibilities offered by the Wallacei add-on by the method of calculating the weighted average of the fitness functions excluding the extreme solutions. The user specifies the fitness function weights by which the solutions are evaluated. The worst fitness values get rejected and the rest of them are remapped to a 0-1 range. The fitness values are then multiplied by the weight factors and all the values for each solution get summed. The solutions are then sorted according to the weighted value they achieved. Best results are then visualized along with their matching fitness values and other parameters such as insolation and view obstruction analysis results.

## RESULTS

MOT was tested on a conceptual design of a residential building on an existing building plot in Warsaw, Poland. In order to select the optimal solution, 6 simulations were carried out using the MOT in 6 generations of 22 solutions each, obtaining a total of 792 possible building forms and placements. Each simulation took around 2 hours 30 minutes to compute on an Acer V15 (2017) laptop with Intel 4720HQ CPU, nvidia GTX960M GPU and 8GB of RAM. The test proves that a simple optimization algorithm can be successfully implemented in modern architectural workflow using consumer-grade hardware.

The design task was also used to calibrate the internal logic and parameters of the algorithm. The specific plot was chosen because it has been the sub-

ject of many student projects providing a database of reference projects. The students' work was used to tweak the algorithm as well as the fitness function weights for the selection process. The algorithm was tweaked so that the results it produced could be considered similar to the classic projects but not limited to them. At the end of the tweaking process a full simulation was conducted.

From each of the six simulations the leading five solutions were chosen based on the selection method described above. One of the best 30 solutions was chosen manually and developed further classically.

MOT automatically generates both analysis data as well as its graphical representation for easy visual result analysis. The insolation and view obstruction results are displayed in 3D, together with a diamond chart representing the solution's fitness values. Such a a representation facilitates quick visual analysis demanded by the assumed hybrid man-machine workflow.

A few of the rejected solutions (Figure 5) as well as the best five results of the first simulation are shown (Figures 6 & 7). Although their fitness values are similar, it can be noticed that at least three very different topologies were generated. Figure 7 shows one of the outcomes in detail: it is a compact L-shaped massing with equal floor plans. The solution utilises the maximum allowed FAR and has only one, relatively short facade with poor insolation.

## DISCUSSION

The algorithm was used to design the initial urban and architectural concept of an apartment building. The first simulation was based on data obtained directly from the zoning plan (without any creative input from the designer). The simulation results complied with the regulations, however they were not completely satisfactory in terms of urban planning. Fulfilling the initial assumption of a hybrid man and machine workflow, further simulations were conducted after adding some urban context driven constraints to the input parameters. In this particular case the designer corrected the input parameter of the building envelope perimeter to force the search for the optimal massing in the northern part of the plot where the vehicle access and the view obstruction condition were better. This example shows how the designer can work with MOT in order to expand the search space, eliminate adverse conditions on the plot or verify new architectural assumptions. During the development of MOT authors have tested automating this stage, but adding another gene responsible for building line changes greatly affected the algorithm's performance so it has been decided to remove this functionality and let the user apply such changes manually if needed. Further hardware development or algorithm optimisations may enable to incorporate the functionality.

Despite the positive results presented in the work, it is clear that at this stage MOT has a number

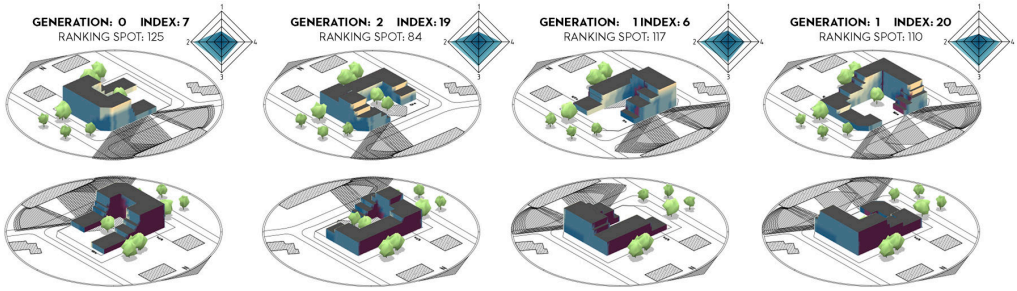



Figure 5
Rejected solutions examples.

Figure 6
Top four simulation results.

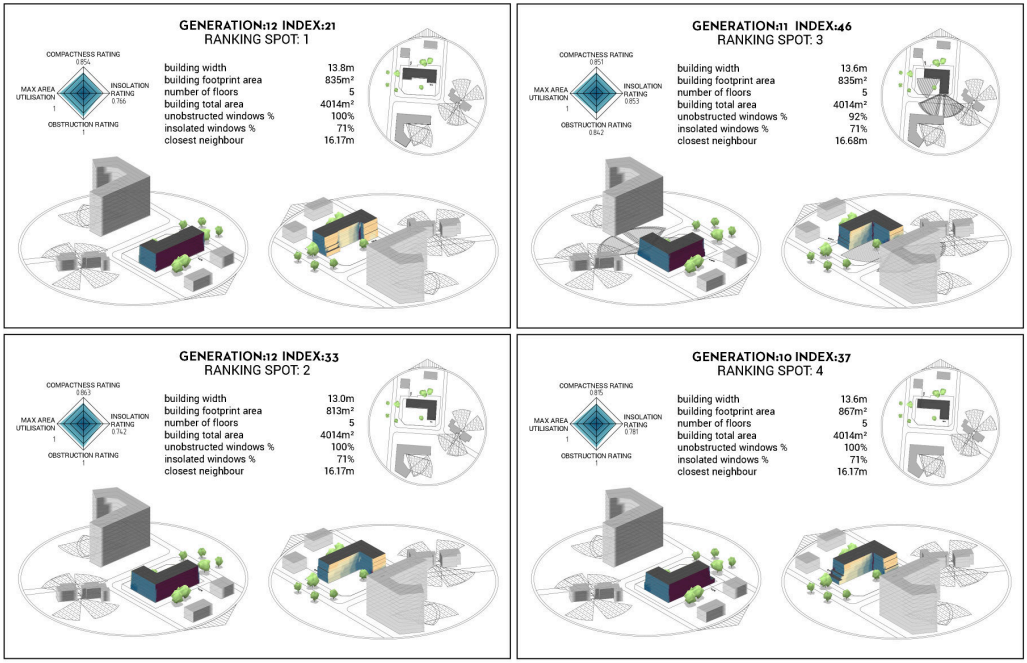
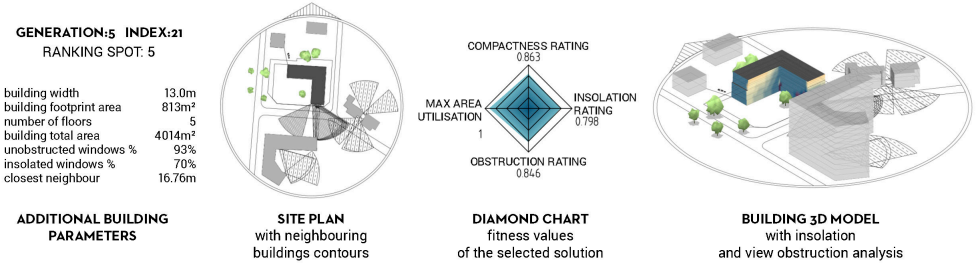



Figure 7
Detailed solution analysis.



of serious restrictions, that primarily include:

- Building form limited to one volume consisting of continuous storeys

It would be particularly important to further develop the functionality of generating more than one building on one plot - such analysis is many times more complex than the analysis of only one building, but its implementation would definitely enrich the functionality of the MOT, while making the algorithm useful in a much wider group of design cases.

- Linking the shape of the building with the shape of the plot or a manually entered building line

Another important improvement of the algorithm would be to introduce more autonomy in locating the building on the plot by adding the ability to change the position and shape of the axis of the building by the algorithm itself. Such attempts were made at an early stage in the development of the MOT; the algorithm had an effect on the values of the building offset parameter from the plot boundaries for each of its edges separately, however, obtaining the appropriate consistency in the search for optimal solutions took much longer than when the functionality was disabled. However, it should be assumed that in the future limitations of computing power will not be such an important parameter when designing similar algorithms.

- Constant building width

MOT is limited by the constant width along the entire length of the building. It would be worth considering introducing a variable width in order to facilitate the solution of more complex design problems.

- Lack of the parking analysis

An important improvement of the algorithm would be the ability to analyze the requirements for parking vehicles and building structural modules strictly connected with the parking modules.

- Lack of the internal division analysis

Currently, only the view obstruction and insolation of the facade is analyzed, assuming some very general premises for apartments (such as the maximum area). It would be advisable to take into account the requirements for the location of apartments according to the desired structure of their size, construction grid, underground parking and the location of staircases.

- Limited typology

In order to simplify the MOT the authors decided to narrow the scope of available building typology to detached courtyard apartment buildings. Preliminary research showed that they are most popular among new residential developments in Warsaw, Poland. In the future the functionality of the algorithm should be extended to generate buildings of other typologies (like tower buildings) as well as non-linear typologies.

- Only flat building plots

MOT performs some of its operations such as view obstruction calculations on a plane, thus it is currently impossible to analyse non-planar plots.

One of the elements to be considered in further development of MOT is the evolutionary algorithm used. Several multi-objective evolutionary algorithms of competing quality are available and their performance in MOT is yet to be determined. The NSGA-II algorithm is one of two multi-objective optimisation algorithms already implemented in grasshopper development environment, the second being SPEA2 available through Octopus plugin. The NSGA-II algorithm was chosen based on King, Deb & Rughooputh (2010) performance comparison where NSGA-II was concluded to be faster by orders of magnitude, although less accurate. The chosen algorithm proved to be effective, although other algorithms can possibly produce the same results faster or avoid the potential local optima traps.

The algorithm was developed in Grasshopper programming environment allowing for a seamless

CAD integration and ease of development. Despite Grasshopper being a flexible development platform it limits the MOT's performance. It would be advisable to rewrite the algorithm's logic from the ground up implementing an intuitive user interface.

Our important finding is that the tools of this kind are likely to be very code-specific, as the evaluation criteria are partially based on following the rules. Due to different legal constraints in different countries this approach is geographically limited.

Nevertheless we believe that the advantage of this study lies in the comprehensive and efficient algorithmization of the preliminary design process with special regard to building codes and zoning regulations rather than in the excellence in the performance of the tool. This study also shows that after the mindful algorithmization and with the assumption of the hybrid repetitive workflow, the evolutionary algorithms can be successfully used to automate early stages of apartment building design especially when only a limited number of architectural typologies are being concerned. In this approach including more housing typologies would be possible probably only by adding another branches of the algorithm with their individual optimisation process and comparing the final solutions.

## CONCLUSIONS

We have presented a new simple optimisation tool that could be successfully implemented in a typical architectural design workflow. The Tool was verified in the conceptual design of apartment building located in Warsaw, Poland. In the course of design works, the Tool generated 792 different solutions of massing - all complying with predefined constraints and assumptions - from which the best 30 were selected by automated tools.

The automated optimisation process proved to be helpful in the early stages of the design development. The ability to rerun the simulation with changed parameters allowed for relatively quick iteration between different building location ideas, and the proposed results were always close to the optimum.

Finally, one of the best performing solutions was manually chosen by architect and developed into a full conceptual design in the traditional way. Selected massing had 99.5% of maximal allowed area, didn't exceed neither the maximal BCR nor the footprint area and was well insolated. The insolation and view obstruction diagrams proved helpful in developing the floor layouts at later stages of the design process.

The Tool assisted the architect in determining the optimal form of the building body, while giving the opportunity to realize his vision. The presented results show that the Tool should be developed further in order to expand its functionality towards making it useful for a wider group of design tasks.

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# Algorithmic Planning and Assessment of Emergency Settlements and Refugee Camps

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*The planning quality of refugee camps profoundly affects the people living there. Because of the short time span allotted to planners due to the state of emergency, camps are often poorly planned or not planned at all. This paper proposes tools and methods developed through computational modelling algorithms that can enhance the design procedure and provide instant feedback about the plan performance to the planner. The developed planning framework allows defining the planning guidelines which will be tested for compliance. The paper also shows case studies of analysing an existing refugee camp.*

**Keywords:** *Refugee camp, shelter, generative design, UNHCR, humanitarian architecture*

## INTRODUCTION

One of the major components of an emergency response is an emergency settlement. In the case of refugees, it can be the refugee camp. Although refugee camps are always advised to be a measure of last resort, we often see the crisis leading to the creation of such camps.

The outlook and location of camps are constrained by certain standards developed by governing entities. This is exemplified by commonplace modernist grid structure layouts. The reason for their ubiquitous presence is the ease of their planning, deployment and monitoring.

An example of such camp is the Azraq refugee camp in Jordan (see figure 1). It is a relatively recent settlement that adheres to the existing guidelines and planning principles. Many refugees that were invited to live there have rejected the invitation. This brings us to the notion that the existing planning strategies still have many shortcomings and should be revised. However, since the research presented in this paper is the first attempt of the authors in the algorithmic planning of refugee camps, the existing norms have been adapted without questioning their efficiency.

There has been a lot of criticism towards the planning principles of refugee camps in recent years. The criticism comes not only from the dwellers but also from the practising professionals in the field. For sure, there is a place for critique. Still, one key consideration must always be taken into account, which is that the planning practice of refugee camps is entirely different from the regular planning practice that an architect might have in a conventional

working environment. The crucial thing that may affect the design is the time. Since it is an emergency and some people are in urgent need of a place to live quite often, the planners and architects prioritise quick and short-term effective solutions as opposed to more deliberately planned and long-term solutions. This paper aims to automate certain tasks in the planning and analysis processes and make the overall process faster and more efficient.

Figure 1
Azraq camp in Jordan (The Red Cross Society of The Republic of China(Taiwan)–Light in the dark - Red Cross Red Crescent hospital in Camp Azraq, n.d.)

As such, there is not much time to take into consideration the wishes of the people that are going to live there, study their background, test whether the given solution is appropriate or not.

This paper aims to bring the advancements in computational design closer to humanitarian architects. Several methods are developed for planning and analysis. The methods include:

- An algorithm that automates the design of a refugee camp based on the supplied standards.
- A method used to analyse the planned sanitation facilities.
- Genetic optimisation of WASH facility placements
- Fire safety analysis of refugee camp through a graph traversal algorithm.

The novelty of this research is the new parametric framework created for both the design and the analysis of the refugee camps. To demonstrate the practical utility the framework is applied to analyse Zaatari refugee camp.

### *Used acronyms*

1. BIM - Building Information Modelling
2. CAD - Computer-Aided Design
3. CCCM - Camp Coordination and Camp Management
4. IFRC - International Federation of Red Cross
5. IOM - International Organisation for Migration
6. OCHA - Office for the Coordination of Humanitarian Affairs
7. UNHCR - United Nations High Commissioner for Refugees
8. WASH - Water, Sanitation and Hygiene

## RELATED WORK

### *Major actors in humanitarian aid*

The first procedure for outlining state of the art was to find and recognise the leading actors in the field of humanitarian response. As it is described in the (see table 1), there are two main entities (so-called clusters) assembled to deal with the issues of settlements and shelters, respectively. Depending on the type of context, whether it is a natural disaster or conflict, a different agency may take the lead of actions such as the IFRC or UNHCR. These two clusters have online databases of resources that contain reports and case studies that closely portray the situation of humanitarian response at hand [2].

| CLUSTER | CONTEXT | LEAD AGENCY |
|---|---|---|
| CCCM | Natural Disaster | IOM |
| | Conflict | UNHCR |
| Shelter | Natural Disaster | IFRC |
| | Conflict | UNHCR |

Table 1
Management matrix from OCHA.

The two clusters together have published resources to guide humanitarian response, including guidelines and standards for architects and urban planners. The developments here are mostly from after second world war. Despite the vast amount of existing work, there is a place for improvement. Such as bringing a deeper understanding of the fire safety measurement elaborated in this paper.

Furthermore, The information needed for architectural and urban design of emergency settlements and shelters is scattered among different documents published by different entities (Ally et al., 2015; Corsellis & Vitale, 2005; UNHCR, 2006, 2007, 2016). Through this research, some of the planning principles and standards from these sources have been used to construct a design framework. This framework contains controllable numerical parameters that the planner can use. Moreover, it performs several automated routines for compliance check and design analysis.

### *Computational planning of emergency settlements*

The most prominent attempt to bring computational modelling to the task of planning an emergency settlement was performed by a joint effort of UNHCR, Stanford University and Ennead Lab [1]. This work was also reflected in details in work by (Huynh, 2015). The key message in both works is the discrepancy between the planned and actual longevity of emergency settlements. However, the project is not open source and the available information about how the developed toolkit is minimal. No public reports on the toolkit performance were found during this research. Nonetheless, it was evident from the available limited presentation materials online that they utilise similar methodology and tools as used in this research. The field of computational architecture has been recently advancing at an increasing pace. After the above-mentioned research by UNHCR and Ennead Lab, more tools have become available that can be beneficial for research and planning in this domain. Namely, the "Urbano" by (Dogan et al., 2018) and the "DeCoding Spaces Toolbox" [3]. They provide many tools for the urban analysis (spatial structure, mobility, centralities etc.) and urban structure generation. These two packages have been identified as state-of-the-art tools and will be addressed in future work for implementation. The advancement in algorithmic humanitarian architecture should be continuous. This paper combines some of the cutting edge technologies in computational modelling and is expected to push forward the state-of-the-art.

It is worth mentioning that recent studies were conducted with the aim to combine speed and seed approaches in the response to a major disaster and the creation of novel settlements, supplying prefabricated units for a speedy answer and implementing them with local materials more appropriate for a specific community (Zanelli et al., 2012). The researchers here have also utilised a similar methodology as presented in this paper.

Another similar work but on a smaller scale was published by (Daher & Kubicki, 2017). This paper is another stepping stone in bringing the computational modelling to humanitarian architecture. However, the model in this work is very simplistic. It is a one-case experimental study using which will always result in similar plans.

## METHODOLOGY

The existing methods of design in humanitarian architecture are still through traditional CAD/BIM. It means that both the design decision and execution are made by the operator. This paper proposes a semi-automated workflow for better and faster planning. All of the operations that are required for the final product are divided into two groups.

The first group is the one where human input is critical such as establishing the standards that the design should follow.

The second group includes operations that can be automated such as the division of the land into shelter plots or checking compliance to specific standards.

The planner defines the boundary and principal roads of the future settlement. Then by reading the standards defined by the planner, the algorithm proceeds to determine the available area for shelter allocation, shelter positions, and more.

In several cases, both the street network and the collection of shelters are described as graphs. A graph traversal algorithm is applied to analyse the graph network of streets and shelters.

### *Tools*

All of the tools and methods are developed with visual/textual scripting in the Grasshopper graphical algorithm editor. The following packages have also been utilised:

- Wallacei - Genetic optimisation
- Shortest walk - Implementation of the A star search algorithm in Grasshopper
- Decoding Spaces
- Lunchbox - Creation of RTrees of the big collection of points for proximity search

## ALGORITHMIC PLANNING OF REFUGEE CAMPS

### *Boundary creation method*

The generative design process of planning a refugee camp starts with the planner input of the curves that represent the boundary of the future camp layout and the road network. Once these are placed, the algorithm detects the areas between these curves taking into consideration the widths of the roads. As a result of this phase, the planner obtains the boundaries of the regions that can be populated with shelter plots (see figure 2).

Later the algorithm recreates an oriented bounding rectangle of these regions. The untrimmed boundaries are subdivided into plots with numerically controlled parameters such as the area per person standard proposed by UNHCR ( see figure 3).

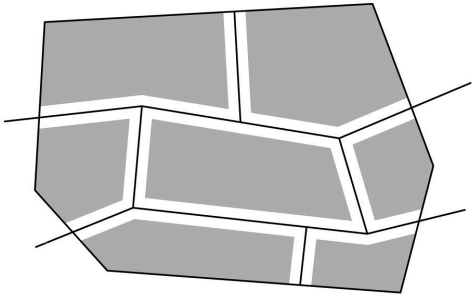


Figure 2
Defining suitable regions

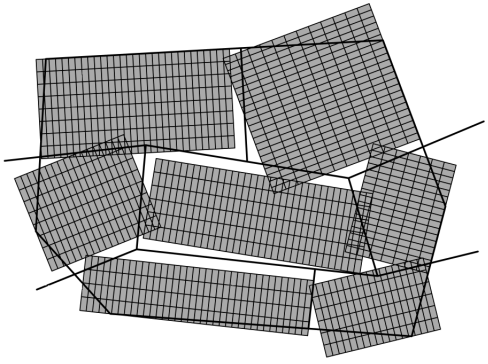


Figure 3
Subdividing untrimmed regions

As a result, some of the plots may be out of the defined boundary, therefore the following logic is implemented to determine which ones should be deleted. If the sum of the distances of the corner points to their closest point in the region is greater than a given threshold, then that plot is culled (see figure 4). The pseudocode for this procedure is presented below.

```
For each plot in plot collection
    For each corner in corner points
        Find the closest point in the
         ↪ region surface
        Measure the distance to the
         ↪ closest point
        If distance > threshold
            Remove the plot from plot
             ↪ collection
```

The threshold used in the algorithm is a numerical value used to control the strictness of culling procedure.

The remaining collection of plots is considered valid. Shelter geometry is generated inside these plots again following the UNHCR standards, and the planner can see the clusters and the quantities of shelters in each cluster (see figure 5).

Figure 4
Culling by the threshold

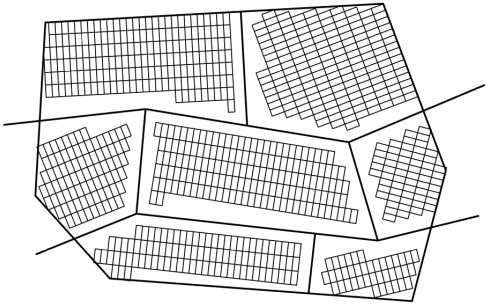


Figure 5
Camp stats

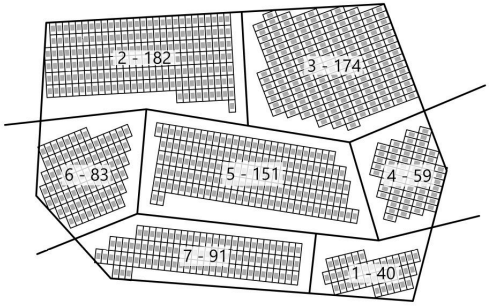
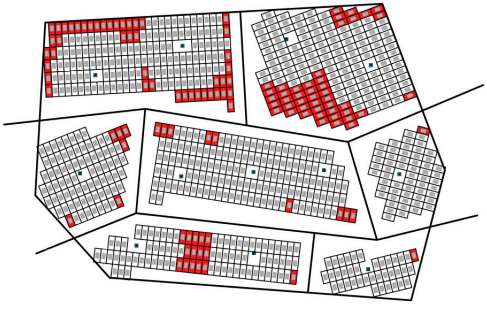



Figure 6
WASH facility reach



### *Infrastructure*

One of the aspects that the site planners should consider in planning refugee camps are the WASH facilities. The arrangement of those facilities is also guided by the defined standards. The standards include the minimal and maximal distance to the shelters, the number of households per facility etc. Here again, the semi-automated workflow takes place. Once the site planner places a point indicating the position of the WASH facility, the algorithm takes out the shelters that are located very close to that latrine. Also, given the maximum distance that the shelters should be from the nearest WASH facility the algorithm determines the closest one for each shelter, then determines whether the distance to that particular point is higher than the standard or not. If the shelter lies out of reach, the sheltered plot is coloured to give visual feedback to the planner (see figure 6).

### *Genetic optimisation*

Several tasks that have no particular necessity for creative design and are rather technical assignments for finding optimal solutions can be automated even further. For this, we have constructed a genetic optimization workflow that has freedom on the decision of placing WASH facilities. The gene parameters are the quantity of the WASH facilities (up to ten units) and their coordinates. For each set of genes, the following three objectives are to be met,

1. Minimise the quantity of the shelters that are out of reach
2. Minimise the overlap between the effective regions for each WASH point
3. Minimise the total length of the constructed piping

Given the positions of the WASH facilities, the piping is constructed following the below-presented algorithm.

```
Indicate the outside supply point
Generate WASH points based on genes
Sort the points based on proximity to
 ↪ the supply point
Create an empty list of pipes
```

```
Draw a pipe from the first point to
 ↪ the supply point
Add the pipe to the list
For each remaining point
    Find the closest point on each
     ↪ pipe in the list
    Sort the found points by distance
    Select the closest one
    Construct a new pipe between the
     ↪ two points
    Add the pipe to the list
```

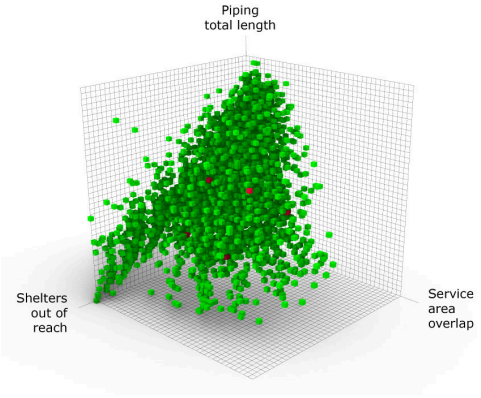



Figure 7
Optimisation attempts: each Cartesian axis corresponds to a fitness goal. Green boxes represent all of the attempts. Magenta boxes show selected solutions.

The multi-objective optimisation algorithm creates a set of solutions that are optimised and can serve as a base model for the site planner to work with. Overall, several thousand attempts of the design were made (see figure 7). From these attempts, the designer can choose solutions that perform the best on either one of the goals or on average. Several compromise solutions can also be selected through the Pareto Front method (see figure 8).

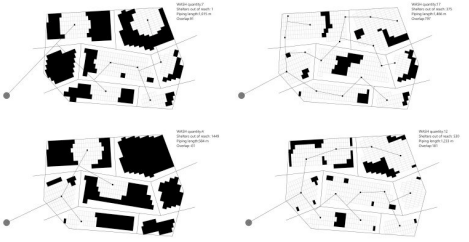


Figure 8
Selected phenotypes

### *Fire safety*

Researchers show that there is a dramatic increase in refugee camp fire occurrences in recent decades (Kazerooni et al., 2016) which depends on settlement planning (Atiyeh & Gunn, 2017). UNHCR defines that there must be a fire break every 300 meters. The presence of such guideline is instrumental since many planners can refer to it. However, there is a certain ambiguity about this guideline. Figure 9 shows an example of shelter placement. For this layout, we can calculate the fire travel distance between the first and the last shelter. One way of doing it would be to take the distance between the two points. Another way would be to create the path of fire propagation. As we can see in the example, one may highly differ from another. In both cases, if the planner is dealing with a settlement with hundreds of shelters, it can be a very time-consuming task to check all potential fire travel paths. This error-prone activity may lead to poor performance of the settlement.

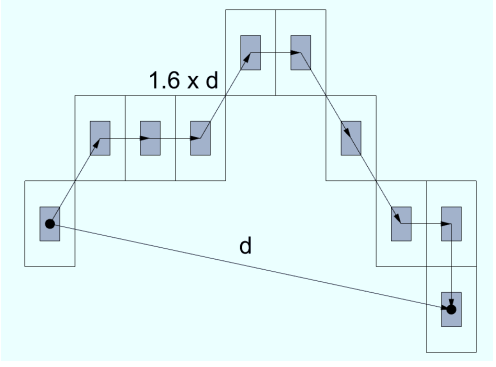



Figure 9
Two methods of fire travel distance measurement

For this planning task, the following algorithm was developed. It starts with the collection of points that represent the placed shelters. Based on their proximity, they are clustered into fire zones (see figure 10).

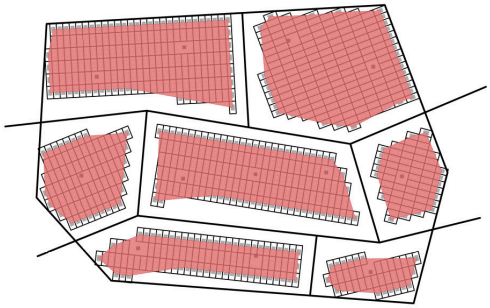


Figure 10
Fire zones

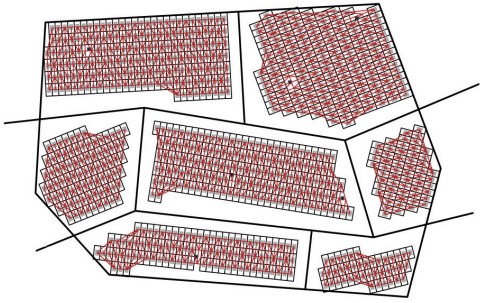


Figure 11
All possible fire propagation lines

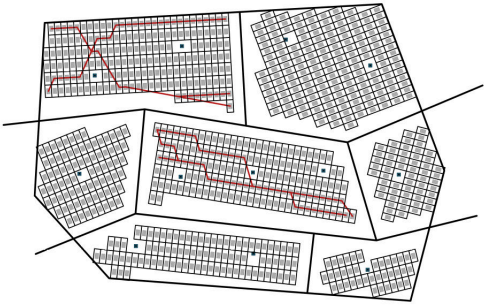


Figure 12
Longest samples of shortest walk routes

Usually, the separation will occur with the placements of roads. The assumption is that if a fire starts in the shelter of a particular fire zone, it cannot spread to other zones. Then for each fire zone, all possible pairs of shelters are separated. With the points of shelters and fire spread lines, a graph network is created (see figure 11).

Then using a graph traversal algorithm, the shortest travel distances are found between each pair. If the found fire travel path is longer than the given value (300 m in this case), the path is visualised (see figure 12). This instant feedback helps the planner to identify the fire risks and to act accordingly.

## DISCUSSION

### *Analysis of existing refugee camps*

With the toolset mentioned above, Existing emergency settlements can also be analysed. As a case study, the Zaatari refugee camp was selected. Open source OSM data is available for this camp. Figure 13 shows the available data which includes:

- Road network
- Zone division
- Several public facilities
- Locations of WASH facilities

### *Existing OSM data*

However, the exact locations of shelters were not available. A uniform distribution was placed in the available regions to serve as a proxy for actual shelters. With the proxy locations, the distance to the nearest wash facility for each shelter was calculated. Then the distances were compared to a UNHCR norm which is 50 meters. With the allocated information about the distances to the closest facility, a colour-coded map was created to show the shelters that do not have a WASH facility close enough to them (see figure 14). An estimated 7% is not compliant to the UNHCR norm. This study is not precise since both the available OSM data and the distribution of shelters are not accurate. However, it proves to be working, and if given better data, it will show reliable analysis.

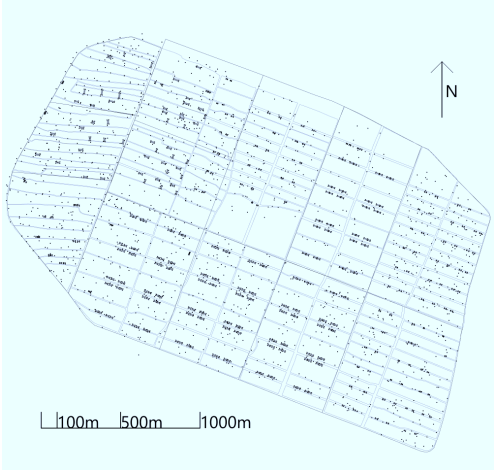



Figure 13
Zaatari camp OSM data

Another issue is fire safety. Following the UNHCR norm of 300 meters maximum distance for fire propagation, the algorithm analyses all potential fire spread lines. Whenever it identifies a case where the fire may travel more than 300 meters, it draws the path between the origin and destination. As we can see, several regions are not compliant (see figure 15).

## FUTURE WORK

As we have discovered, more and more urban planning and optimisation algorithms become available for architects and urban planners such as the De-Coding Spaces [3] and Urbano (Dogan et al., 2018). Both provide many methods that can be utilised to make advancements in the computational design of refugee camps. Further implementation of those packages can include:

- Generation of street networks
- Analysis of road network quality
- Hydrology planning
- Analysis of public amenities

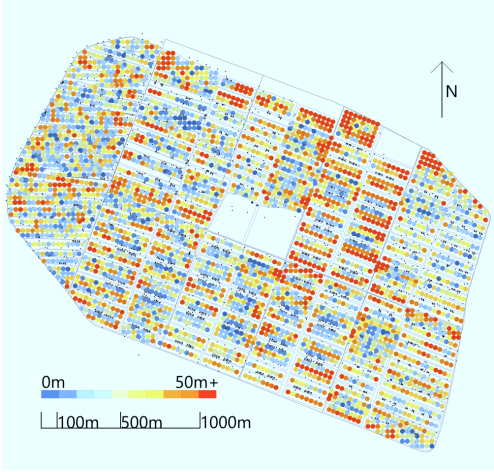



Figure 14
Latrine reach analysis

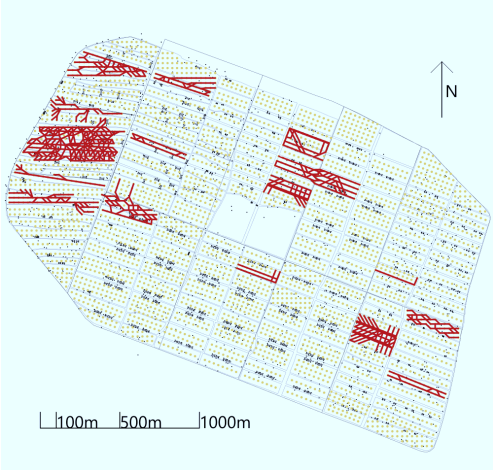



Figure 15
Fire propagation lines

### *Web user interface*

As it normally it happens in the emergency response, the solutions must be low tech in a way that anybody should be able to use it. In this regard, our research presented in this paper utilises computational modelling software and algorithms that not many field site planners are able to use. But in its essence, the problem can be narrowed down to a simple set of inputs that the user needs to supply and the outputs that are needed. To streamline this process we are building a web user interface of the presented algorithms using Giraffe (Gardner et al., 2020). Giraffe is a web application that allows Grasshopper scripts to be deployed online via an intuitive interface (see figure 16). This allows non-experts to utilize the script to solve problems without special training or software licenses. This technology is highly relevant for refugee camps enabling them to be designed quickly and with detailed automated analysis ensuring maximum safety for occupants.

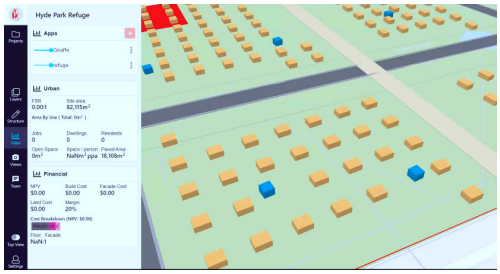



Figure 16
Web interface

## CONCLUSION

Computational modelling in humanitarian architecture is a relatively new field. This paper presents tools and methods that can be implemented by planners for better design and analysis of refugee camps. We used the existing norms and knowledge to develop a design framework which automates certain tasks and provides real-time feedback about the design performance. Nevertheless, the results shown here are one of the first attempts in academia to adapt computational modelling to the tasks of planning for refugees.


## ACKNOLEDGEMENTS

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# D1.T5.S3. EDUCATION AND DIGITAL THEORY – ETHICS, CYBERNETICS, FEEDBACK, THEORY

# Teaching Digital Design Principles to First Year Design Students

## *A methodology based on direct experimentation with physical construction assemblages*

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*An educational methodology is presented that introduces basic digital design concepts to first year design students. The methodology differentiates between four fields in design thinking namely Form, Function, Context, and Structure/Materiality and focuses on Structure/Materiality that is approached as an assemblage of components. Components are categorised in respect to their geometric and structural qualities with reference to the elements of `point', `line', `surface' and `volume'. Components are interconnected to corresponding design techniques that are used in order to compose complex forms and are outlined by a rule of composition. The primary technique of `point' structures is based on the notion of multiplicity and repetition. `Line' assemblages introduce to the concept of load bearing structures and they can effectively describe hierarchical associations. `Surface' elements are used to explain the results of transformational processes upon structural behaviour. `Volume' techniques refer to the notion of integration and directly affect the overall performance of the structure. For each one of these elements, the students are asked to work directly on physical assemblages with ready-made components which are chosen in respect to their structural characteristics and to describe explicitly the whole process in drawings and diagrams.*

**Keywords:** *Digital design principles, Experimentation, Assemblages, Components*

### *Introduction - Background*

The use of digital technologies gradually becomes a common tool for architectural discourse and it is widely used by architecture students during their studies. Access to parametric and algorithmic design tools, and fabrication technology, changes and evolves the architectural design process. However, while the organised teaching of digital design is found in specialised postgraduate courses, in undergraduate architectural education the usual teach-

ing methodology is still the traditional design studio where the educational model is the simulation of the design practice (Papadopoulou et. al, 2007). Digital tools are taught as auxiliary drafting or modelling tools. According to this educational model, design process is divided in stages that usually starts with the theoretical analysis of a given program and continues with the interpretation of site and context conditions, and then a schematic design is initiated that is based on existing typologies or, as it is quite often recently, on precedents as images found through the internet. Explorations are supported by paper-based sketches. When an architectural form is stabilised, design development begins which is supported by computer drafting, modelling and imaging tools.

Scholars in design pedagogy notably argue that digital design is a unique field of design endeavour relying on its own theoretical sources and methodologies and promoting its distinctive ideology and formal content. Digital design includes new concepts about the meaning of form, an alternate understanding about the nature of function, materiality and performance, and new generative and transformative processes that are used to progress in design (Oxman, 2008). All these indicate a need for new educational models and a different pedagogy. Of course, a lot of schools have specialized courses particularly during the later stages of architectural education that introduce and explore the potentials of digital design. Students realize at this late stage that digital design is a whole new enterprise of design thinking and not just a technical tool that support and enhances a standard conventional practice. As a result, there may be a number of students that are thrilled with the new prospective and continue to study it in dedicated postgraduate courses. Yet, the greater number of them simply returns to their known practice and digital design for the non-specialists still remains a technical subsidiary field.

This paper presents the course "Introduction to Architectural Design" at the School of Architecture of Thessaloniki. The course takes a transversal approach to the problem mentioned above. It introduces to first year design students an educational methodology that describes the totality of design activity but relies on design knowledge and concepts that derive mainly from the field of digital design. It utilizes design experimentation with simple techniques that refer to the analytical, constructive and ontological way of thinking that characterizes digital design without the necessity of using computerized systems or understanding their technicalities.

## *Description of the course (case study) - Basic principles*

The course adopts a descriptive and generalized view about design. It explains the four major fields of interest that affect design and outlines them as the field of Function, Context, Form and Structure/Materiality (Bielefeld & El Khouli, 2013). Design is defined as the effort to achieve a fit between the tendencies and requirements, the constraints and possibilities that arise within these fields. Thus, design is not seen as a standard problem-solving routine in which the final outcome is entailed by some given objectives. Instead it is a personal and distinctive highly dynamic cognitive activity in which instances of information within the above-mentioned fields and the interpretation by the designer plays an important role. Function and Context are abstract fields that are difficult to attain. They are conditioned by theoretical, varied and imperceptible knowledge sometimes outside the area of design. Form and Structure/Materiality are more tangible and concrete fields as the knowledge that condition them can be more explicitly expressed and has to do with the physical counterpart of design.

As stated earlier, the standard conventional design process starts with resolutions within the field of Function, taking into account Contextual restrictions, and continues with explorations about the outline of a Form and the adoption of a Structural scheme in order to accomplish the constructability of the designed object. However, this is not the case for digital design. For digital design these fields are not as distinct as they appear in the sequence above.

Form and Structure, for example, are bond together with geometric associations that allow modifications in one field to trigger changes in the other and vice versa. This supported a whole new endeavour to flourish, known as form-finding. This initiated by the experiments of Frei Otto (Nerdinger, 2005) and continues today with the approaches of Digital Tectonics (Leach et. al, 2004). Furthermore, the process-oriented character of digital design and the parametric descriptions of the designed object allow us to assume that digital design works in a continuum and permits cross layer assertions and cross scale judgements to be made.

As such, at the first part of the course "Introduction to Architectural Design" students are asked to approach the Structure/Materiality field of design. In addition to what stated above, the reason for doing so is to unlock the creative potential of students who when entering the school come with a series of presuppositions, reservations and clichés about architectural design and form that lead them to highly conventional and superficial results. The focus on the activity of form-finding directs them to experimentation rather than to the adoption of ready-made solutions. Later, during the second part of the course, the students will deal with the rest of interest in design: Form, Function, Context.

### *Method of attaining a structural model*

Structure is approached in terms of components (Zarzycki, 2012). Component-based design is a well-known approach in digital tectonics. It was chosen as it brings a direct attention to materiality and process in design. Furthermore, component-based design can be realized by students with limited knowledge on design theories and focuses on the actual and the performative aspects of design. It allows students to start experimentation from the beginning of the educational process without the hesitations associated with big scale decisions. Above all, it enhances their creativity and spatial thinking and grows their interest on the making of architecture.

Four different categories of components are introduced to the students. These are chosen in relation to the geometric and structural qualities, the techniques that are used to interconnect them during construction, and the potentialities of the outcome. These categories refer to the basic geometric elements of point, line, surface, and volume. For each of these categories, students are asked to use ready-made components and to construct a physical assemblage. The assemblage is constructed straight in real scale without the use of prior drawings. Different components are used for the different categories. Small pieces of wood or plastic, seeds, balls, etc. for structures that refer to point, sticks of wood, wires, strings, etc. for linear systems, large sheets of paper, textiles, plastic sheets, etc. for structures that refer to surface, and only in the case of volume students can construct solids as components. Then there is a great deal of experimentation in order to find out the structural properties of the components and to define the technique that is used to combine them and to create stable assemblages. Students are asked to use a single interconnecting technique for each assemblage but variations are welcome. The whole construction process is documented and presented in posters and diagrams. Emphasis is given to provide an explicit description of the logic, the rule or the process that underlies the interconnecting technique.

Point-like components refer to architectural forms that are made with small scale elements like bricks, stones, small pieces of wood, etc., without the use of a load bearing frame. The main characteristic of these structures is the notion of multiplicity and repetition. They are conditioned by a rule according which pieces are put together. Rule-based design allows the generation of spatial complexity based on simple principles (Valena et. al., 2011). The result is a usually a surface that tends to display patterns. The surface is theoretically borderless unless edges or shapes are imposed by another rule at a higher level. Therefore, rule-based structures are good demonstrations of the notion of 'field'. As the rules act at a low level, clear conceptions of the process reveal unforeseen formal layouts, in a bottom-up fashion,

which are structurally interesting and systematically coherent.

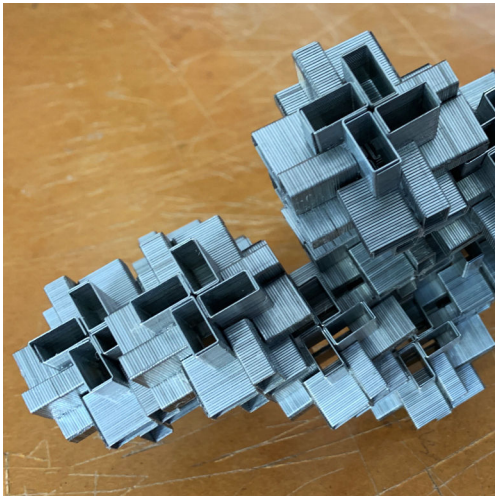


Figure 1
Assemblage with point-like components

For linear components the reference is architectural forms that are made either from rigid elements, such as wooden sticks, iron bars, etc., or soft and elastic ones, such as wires, ropes, strings, etc.. The main characteristic of these structures is that different elements play a different role within the whole structure and, therefore, are good demonstrations of the notion of hierarchy. The whole structure can be described as a series of hierarchical associations. In addition, the issue of structural articulation is discussed that refers to the constructive qualities of the connection between the different elements. Linear structures are actually that most common types of load bearing frames in architecture and their discussion includes issues on structural behavior such as with the notion of tension and compression. Tensegrity constructions, in particular, refer to a specific structural system of isolated components under compression inside a network of continuous tension, arranged in such a way that the compressed members (usually bars or struts) do not touch each other while the prestressed tensioned members (usually cables or tendons) delineate the system spatially. They were explored by Buckminster Fuller and they are very popular in digital design studies (Buckminster & Marks, 1960). A specific kind of linear systems is the weaving systems. Weaving systems have been studied extensively in digital tectonics. They are effectively rule-based systems in which two distinct sets of threads are interlaced at certain angles to form a fabric or cloth. Other methods are knitting, crocheting, felting, and braiding or plaiting. An interesting technique is when the combination of different rules, or variations of the same rule, are used on the same surface. This produces varied and unexpected effects (Spuybroek, 2009).

Figure 2
Linear components

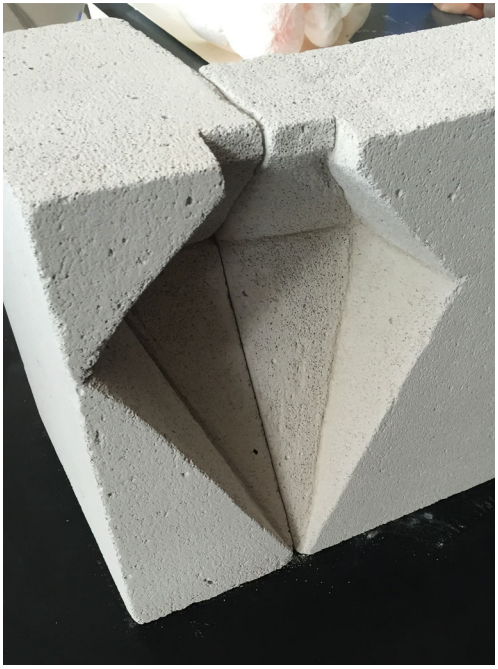
In constructions that use surfaces as structural components the main attribute is the differentiation in spatial behavior that each single element attains in respect to conditional aspects. In other words, a single surface can be an 'inner' wall or an 'outer' wall, can be a 'roof' or a 'floor', depending on its relation to other elements. Hence, surfaces are appropriate to study the notion of continuity. The exploration of the new tectonic and economic potentials of con-

tinuities of all types (spatial, programmatic, visual, technical, environmental, formal and symbolic) was brought about by the merging of computational design and digital fabrication (Lynn, 1993). In relation to structural qualities, it is quite important to note the different structural behavior that single elements attain when simple transformational techniques are applied to them such as bending, stretching or folding. Thin surfaces can become rigid and self-retained. A whole new area of potentials arises when soft elastic surfaces are used in combination with control points that regulate their tension and geometry. Frei Otto has studied as great variety of these constructions and used them for the design of the München Olympic Games shelters (Otto, 2009).

Figure 3
Surface assemblage

Figure 4
Volume assemblage

Finally, constructions that refer to volume use bigger scale solids as components. Solids are made from cardboard boxes, balls or polystyrene blocks and the students were asked to compose an assemblage using multiple times a single transformation. As volumetric constructions have been used extensively in architecture, there are a lot of compositional practices and solid transformations which are worthwhile studying. Volumetric transformations are difficult to be defined by descriptive geometry and have been accommodated in early modelling software. Boolean operations (volume union, subtraction, intersection) were among the first techniques used in 3d modelling in order to create complex forms. More complicated transformations, such as packing, draping, stacking, bending, stretching, twisting, splitting, etc., are explored by the students in physical assemblages. Yet, such constructions cannot actually be seen as structural systems. Volumetric compositions tend to be closed and integrated and they are usually approached as finalized forms.



### *Structural model and design process*

The second part of the course approaches the rest fields of interest in design: Form, Function, Context. A new brief is given to the students requiring the design of a light construction to accommodate outdoor activities in the University campus. Students are asked to use as reference one of the assemblages already made and to develop the design based on the same structural and formal principles. The students continue to work on physical models but now issues of scale, access, orientation, size, distribution, etc. are discussed. They have also to confront a realistic brief on a real site with all the restrictions and consequences that this entails. Yet, they retain a structural model that is used as a basis for the development of the design. As with the previous part of the course, most of the teaching within the studio follows a direct dialectical tactic with one-to-one tutoring and direct work with the assemblages. As such, digital design concepts are not defined and explained beforehand but they are approached as they are revealed during design and discussed with the tutors. This might look a little vague and dissimilar. However, in most of the projects the notion of design as a system whose properties arise from the relationships between its parts is discussed. And of course, the notion of a parametric structure as a core frame upon which the rest of design builds up. Nevertheless, the bigger differences from the conventional approaches discussed in the introduction of the paper refer to four major shifts which are not explicitly discussed with the students, but play an important role. Firstly, the abandonment of the modernistic design ontology that is predicted by formal, definite and typological knowledge. Secondly, the merging between conception, generation and production within a single medium. In our case this was the physical assemblage (to the extent that it encompasses design changes). In digital design, the medium is a central dynamic digital model that holds all design information. Thirdly, the relief of design from strong concepts of representation. Image is not any longer the central part of design and precedents play a limited role as directing forms. Finally, the development of design is based on emergency and transformational processes that occur through experimentation and the direct contact with the assemblage. Development is not only the refining and amplification of already conceived forms.These shifts point out to a new orientation in design education roughly defined as "digital design thinking" that may become the core of a new pedagogy in design (Oxman, 2006).

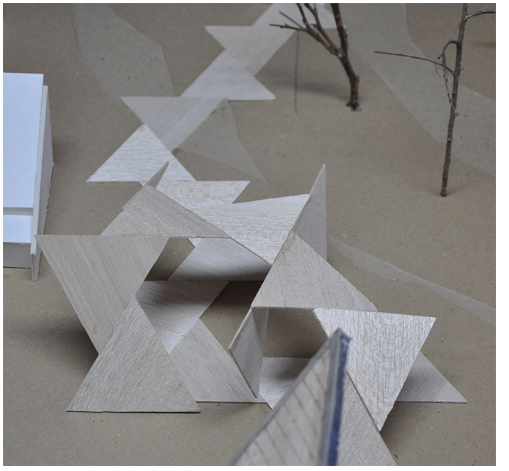


Figure 5
Final project 01

Figure 6
Final project 02

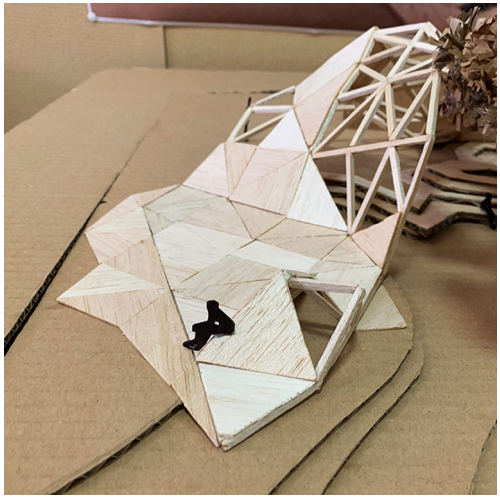


Figure 7
Final project 03

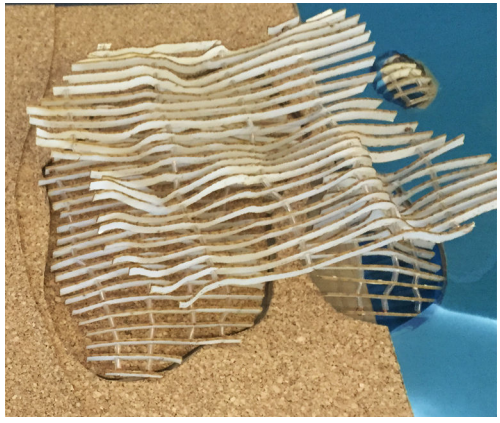
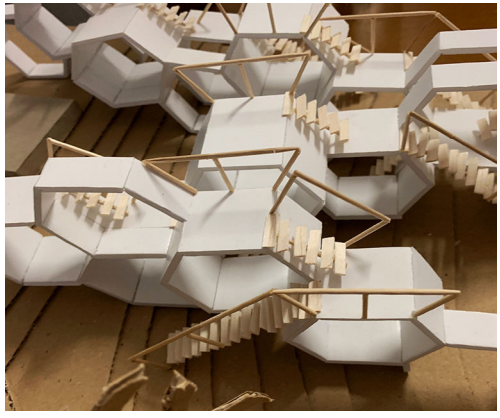


Figure 8
Final project 04



### *Conclusions*

To sum up, the architectural course presented, introduces basic digital design concepts to first year design students. The educational methodology differentiates between four fields of interest in design, namely Form, Function, Context, Structure/Materiality, and proposes a teaching tactic in which the students approach firstly Structure/Materiality. A structural model in the form of a physical construction assemblage is used that is based on geometric components. Design concepts and techniques appear and discussed through experimentation and the direct contact with the assemblage. At a second stage, the rest of design fields are approached. It is quite difficult to evaluate the success of the educational experiment in respect to digital design knowledge that the students gain. At a first glance, the students begin to support their projects by arguing on the logic of their designs, the clarity of the principles and the coherence of the rules. This seems to be a goal as usually students at this stage tend to refer only to personal preference when supporting their projects. It would be good though to observe the same students at a later time and courses that explicitly present digital design principles and methods. However, this is difficult with the current structure of the educational program of the school and could be addressed with additional dedicated research. Nevertheless, the focus on the making of architecture and on form-finding activity and the experimentation with physical models and explicit rules of composition seem to unlock the creativity and innovation and give quite impressive results from students with limited experience in design.

***Acknowledgments***

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# Concept Learning Through Parametric Design

## *A learning situation design for parametric design in architectural studio education*

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*Over the past few decades, architectural practice and, consequently, the design studio have been increasingly challenged. Indeed, the development of digital tools and parametric design, in particular, has given rise to a new type of architectural knowledge. Among the IJAC publications over the past three years, we highlight the current diversity of vocabulary used to discuss this knowledge and develop why we focus our study on conceptual knowledge. We then report a learning situation through studio design education. This paper finally presents the steps developed to measure this knowledge and hypothesizes on the future work needed in order to have relevant quantitative results. The purpose of this paper is to observe the evolution of students' understanding when shifting from a traditional teacher-student relationship to an engaging learning environment, considering the specificities of parametric, and not to suggest a strict method to follow when learning parametric. This could guide teachers to adapt to their own situations.*

**Keywords:** *Pedagogy, Learning, Parametric Design, Form Study*

## INTRODUCTION

According to various academics, the difference between traditional architectural design and digital architectural design is significant (Oxman, 2008). As a result, in research on digital design in general, and parametric design in particular, the necessity to update the traditional pedagogical methods used in architecture education is frequently addressed (Varinlioglu et al., 2017). In order to address this update effectively, in this study both the content and the context of education are considered.

Firstly, on the one hand, parametric designers need to process more than the traditional content of the architectural curriculum (Oxman and Gu, 2015). For example, in addition to fundamental architectural principles, these designers need to train skills related to parametric design (Oxman, 2017). Among these skills, some are stable (e.g. mathematics) while some are rapidly evolving (e.g. software-specific

knowledge) (Jancart and Stals, 2019), which results in a constantly evolving and non-exhaustive list of educational content (Jabi, 2013; Pottmann et al., 2007; Woodbury, 2010). On the other hand, Woodbury (2010) claims that parametric designers need a 'different' or 'new' kind of knowledge compared to traditional architects. In his book 'Elements of Parametric Design' he explains this knowledge through a thorough list of parametric concepts (e.g. points, vectors, and equations), and the introduction of various knowledge types (e.g. technical knowledge, mathematical knowledge, and geometric knowledge). Accordingly, as a result of the complexity of this new knowledge and the expanding list of information and skills required to practice parametric digital design, effective designs of educational programmes are not necessarily easily developed.

In order to consider the so-called 'New Knowledge' in a broader range of publications, IJAC articles (International Journal of Architectural Computing) published in 2018, 2019, and 2020 (Volume 16 and 17 issues 1-4, and 18 issue 1) were analyzed. As a result, a total of 29 articles were used. In each article, the names of the knowledge types as introduced by authors were highlighted. Next, the number of articles that mentioned knowledge types by the same name were added. For example, when an article mentions a knowledge type once or several times, the count is one. When the next article mentions a knowledge type once or more times, the count is two.

As presented in Figure 1, a total of 41 types of knowledge were mentioned in the articles reviewed. Of these knowledge types, 36 types were not repeated in other articles, three knowledge types were repeated twice (i.e. domain knowledge, domain-specific knowledge, and local knowledge), one type of knowledge was repeated three times (i.e. design knowledge), and one type of knowledge was repeated 4 times (i.e. new knowledge). Based on this study, in research in architectural computing, many knowledge types are considered. However, there is limited consensus on the definition and designation of knowledge types. As a result of this disunity of knowledge type definition, multiple consequences become apparent. For example, by using various definitions, the comparison of research output becomes less efficient. Additionally, without a consensus on knowledge types, a broadly-supported update of traditional pedagogical methods becomes a challenge.

Secondly, as a result of the continuous introduction of new knowledge into parametric design research and education, in this study, the traditional teacher-student relationship (Hooks, 1994, pp. 13-22) is revised. According to Hooks, in this traditional relationship, the teacher is considered as an active knowledgeable participant, and the student as a passive listener. In this context, teaching is one-directional, in which knowledge is transferred from the teacher to the student. Consequently, learning cannot be effective without the presence of a teacher. In parametric design education, this teacher-student relationship is likely to be ineffective. As a result of the continuous change in parametric design tools and procedures, teach-

| Nr. | Description | Use | Nr. | Description | Use | Nr. | Description | Use |
|---|---|---|---|---|---|---|---|---|
| 1 | Architectural Knowledge | 1 | 15 | Domain knowledge | 2 | 29 | Possibilistic Knowledge | 1 |
| 2 | Base knowledge | 1 | 16 | Domain-Specific Knowledge | 2 | 30 | Probabilistic Knowledge | 1 |
| 3 | Basic Knowledge | 1 | 17 | Empirical Knowledge | 1 | 31 | Procedural knowledge | 1 |
| 4 | Best Knowledge | 1 | 18 | Expert Knowledge | 1 | 32 | Programming Knowledge | 1 |
| 5 | Broad Knowledge | 1 | 19 | Extensible Knowledge | 1 | 33 | Propositional Knowledge | 1 |
| 6 | Collective Knowledge | 1 | 20 | Human Knowledge | 1 | 34 | Scientific Knowledge | 1 |
| 7 | Common Architectural Knowledge | 1 | 21 | In-depth Knowledge | 1 | 35 | Significant Knowledge | 1 |
| 8 | Comprehensive Knowledge | 1 | 22 | Intimate Knowledge | 1 | 36 | Sound Knowledge | 1 |
| 9 | Contemporary Knowledge | 1 | 23 | Knowledge for | 1 | 37 | Tacit Knowledge | 1 |
| 10 | Deeper Knowledge | 1 | 24 | Knowledge how | 1 | 38 | Technical knowledge | 1 |
| 11 | Descriptive Knowledge | 1 | 25 | Knowledge of | 1 | 39 | Theoretical Knowledge | 1 |
| 12 | Design Knowledge | 3 | 26 | Local Knowledge | 2 | 40 | Valuable Educational Knowledge | 1 |
| 13 | Detailed knowledge | 1 | 27 | Mathematical Knowledge | 1 | 41 | Valuable Knowledge | 1 |
| 14 | Digital Knowledge | 1 | 28 | New Knowledge | 4 | | | |

Figure 1
Overview of the recurrence of knowledge types in the 29 IJAC publications selected in 2018, 2019, and 2020.

ers are challenged to keep up with these developments, which pressures the traditional top-down educational approach. So as to address this situation, in this study, aspects from the problem-posing educational model of Freire (Freire and Ramos, 2000) are considered. In this model, the traditional teacher-student relationship is liberated, by introducing a two-directional teaching-learning approach. By dissolving the teacher-student contradiction, both teachers and learners become active participants in the educational context, opening up teaching and learning opportunities for both teacher and student. Therefore, to respond to the request of various scholars (Kotnik, 2010; Oxman, 2008) for the formation of a theoretical framework to introduce digital design (e.g. parametric design) into a pedagogical agenda, three aspects are discussed in this study. Firstly, the knowledge type as referred to as 'New Knowledge' is further elaborated and framed. Secondly, a two-directional learning situation design to construct this type of knowledge is explained, and a preliminary learning situation is designed and developed. Additionally, a learning situation design aiming at this type of knowledge is tested. Finally, we discuss and conclude our findings.

## KNOWLEDGE DIMENSIONS

As discussed in the previous section, knowledge as required in parametric design education and practice is a composite of many. Depending on the field of research, or mode of education, various knowledge types are addressed. Although in research a wide range of knowledge types are introduced (Figure 1), the vast majority of vocabulary used does not directly overlap with frameworks used in lifelong learning (European Commission, 2018), cognition (Anderson, 2015), or pedagogy and didactics (Illeris, 2007; Krathwohl, 2002). This limited overlap suggests that these types are developed independently of these domains, which complicates the development of a shared pedagogical agenda, and the design of effective educational programmes.

With the intention to organize the various knowledge types as used in parametric design education, and define learning outcomes for educational programme design, the knowledge dimension defined by Krathwohl (2002) is used. This dimension is a revision of the taxonomy of Bloom (Bloom, 1984, p. 18), and serves as a widely used framework in pedagogy and learning design (Anderson and Sosniak, 1994). In the revised taxonomy, four categories are distinguished (i.e. factual knowledge, conceptual knowledge, procedural knowledge, and metacognitive knowledge). (1.) Factual knowledge consists of the basic aspects a learner must know to become familiar with a discipline. (2.) Conceptual knowledge consists of the interrelationships a learner has formed between the aspects of factual knowledge. (3.) Procedural knowledge consists of methods of how to do something. (4.) Metacognitive knowledge consists of awareness and knowledge of the learner's personal cognition. In this study, factual, conceptual, and procedural knowledge are considered.

In order to frame the three dimensions of the revised taxonomy into parametric design, three learning outcomes are introduced. Firstly, when a parametric design learning programme mainly aims at factual knowledge, the learner can reproduce definitions for aspects like functions, variables, and vectors. Secondly, when a learning programme emphasizes the formation of conceptual knowledge, the learner develops mental models in which aspects like functions, variables, and vectors are interrelated. Finally, in the case of learning programmes that aim at procedural knowledge, learners will, for example, be able to parametrically define a cube. Consequently, once these three dimensions are recognized, learning programmes need to be designed particularly to meet the intended learning outcomes.

In order to consider learning outcomes used in contemporary computational research and education, and to frame the so-called 'New Knowledge' into one of the knowledge dimensions, the number of analyzed IJAC articles is extended with the issues of volume 14 and 15. As a result, based on the is-

sues from 2016 to 2020, five definitions of new knowledge were introduced. The first definition refers to new knowledge in terms of age (Karakiewicz, 2020). In this case, knowledge of recent years is considered. In the second and third definitions, new knowledge is considered to be the result of experimentation. Firstly, Symeonidou (2016) considers new knowledge as a result of knowledge construction and reflection. Based on constructivist learning theories, she states that learners construct knowledge through experience, critical reflection, and experiment replication. Secondly, Trilsbeck and colleagues (2019) consider new knowledge as a result of intervention, disruption, and informed experimentation. In the fourth and fifth articles, new knowledge is formed through a process of mapping. Firstly, Tosello and Bredanini (2017) relate new knowledge to concept development. Secondly, de Vasconselos and Sperling (2017) consider new knowledge as the result of research activity, mapping complexities, network visualization, and the collection and connection of dispersed information. When the second to fourth definitions of new knowledge are framed in the four knowledge dimensions, the second and third inform the educational process more strongly on the mode of learning and the fourth and fifth on the learning outcomes. Nevertheless, all four definitions can be considered in relation to conceptual knowledge. Therefore, in the following section, conceptual knowledge is further elaborated and linked to these studies. Additionally, the ways to form this type of knowledge are introduced and explained.

## KNOWLEDGE CONSTRUCTION

As discussed in the previous section, conceptual knowledge consists of a network of relations between factual knowledge aspects. Through these relations, learners organize information into mental models so as to differentiate particular aspects based on their properties (Klausmeier, 1973). For example, when a novice learner in parametric design has formed a mental model of geometry, the student understands that lines, planes, and solids are included, and functions, values, and variables are not. Accordingly, based on particular properties, each learner forms their individual structure of understanding. Furthermore, as introduced by Tosello and Bredanini (2017) and Vasconselos and Sperling (2017) in the previous section, novel experiences are linked to this structure, for the conceptual knowledge to expand, and mapping visualization exercises can be applied to structure and explain. As a result of this individual process, the structure of mental models differs from one designer to the other and varies per stage of development. For example, when the mental models of novice and expert designers are compared, the following distinction can be made. Regarding specialized conceptual knowledge, the mental model of the novice designer is relatively small and rudimentary. Firstly, as a result of the smaller size, novice's mental models have limited coverage in solving specialized design problems. Secondly, because of the rudimentary characteristics, design problems are often more consciously and specifically defined. By specifying the problem situation explicitly, appropriate knowledge can be constructed as a means to solve the problem in a structured manner (Wankat and Oreovicz, 2015, p. 68). Compared to novice designers, expert designers tend to work with larger mental models of a more general character. Provided with a mental model of highly structured concepts, the expert is able to access information associated with the problem more efficiently, and therefore solve design problems more effectively (Simon, 1996, pp. 85-94). In parametric design for example, as a result of efficient knowledge structure, expert designers spend limited time on the parametric model construction and focus on the use of the parametric definition in design problems. Because of the rudimentary knowledge structure of novice designers, generally, a large part of their studio time is spent on the construction of parametric definitions, which leaves them with limited time to use their programs in problem-solving (Gallas et al., 2015). Consequently, as the result of the differences in men-

tal models between novices and experts, different teaching and learning approaches are often favored.

When the new knowledge teaching strategies of Symeonidou (2016) and Trilsbeck and colleagues (2019) are considered, mainly two approaches can be distinguished. The first teaching and learning approach is through experience, disruption, and reflection. In pedagogical research, this approach is often referred to as learning through trial-and-error (Wankat and Oreovicz, 2015, p. 69) or try-it-and-see (Hicks, 2004, p. 2). In this mode of learning, individual conceptual knowledge is formed through design and practice first. Then, the individual knowledge is structured and explicated through critical reflection and experiment replication, to verbalize and align conceptual knowledge. The second learning approach is learning through informed experimentation. In this process, specific tools and strategies used by expert designers are introduced first (Cross, 2011, pp. 3-28). Then, these tools and strategies are applied to design exercises. Both approaches have their opportunities and challenges. For example, the first approach allows the learner to progress at their own pace, using their preferred learning style. As a result, various strategies are formed, and novel approaches are introduced. Nevertheless, individual critical reflection is time-consuming, which makes this approach more feasible for smaller groups. The second approach supports the learner by a framework to structure their design process. Subsequently, all participating learners follow a similar track, which makes learning outcome comparable, and peer learning more efficient. Nevertheless, by aligning the design process, deviations are less likely to happen, which reduces the change of unexpected innovation. The courses addressed in this study are limited in time and include a larger group of students. Therefore, for the preliminary learning situation design, the second approach is emphasized. Although reflection moments are introduced, the design process is set, and choices are restricted. To measure the effectiveness of this design, in the following section, the preliminary learning situation is introduced and tested.

## PRELIMINARY LEARNING SITUATION DESIGN

To test the learning approaches as introduced in the previous section, the course "Digital Culture and Generative Processes of Form" is used. This course is a part (2ECTS) of the Master Program of the Faculty of Architecture (ULiège, Belgium), and aims to develop formal and material research. The main assignment of the project was to design and develop a lamp. For this course, a framework to structure the student's design process is defined. Accordingly, learners followed a similar pathway, which makes the learning outcomes comparable, and facilitates peer learning. The course covered in this study was delivered over a 6 weeks period at a rate of 4 hours a week. The group of participants was composed of 21 students in pairs.

For the preliminary learning situation design, a methodology to teach and evaluate conceptual understanding is proposed. In this learning design, firstly a spatial model for parametric design is submitted by the student. Next, multiple parametric concepts are introduced to support the development of this model into a physically built design. Accordingly, the effectiveness of the learning design is measured by the improved conceptual understanding between the initial and the finalized model. For this preliminary test, visual observation, and student report analysis are used.

In order to introduce a two-directional teaching-learning approach, in the Preliminary Learning Situation for Model-Centered Parametric Design Education (PLMP) as presented in Figure 2, the design process is centered on physical models or form-studies. By using physical models, a medium is introduced that allows two-directional teaching and learning without dependency on digital specifics of coding and algorithm creation. As a result, the PLMP distinguishes the following seven phases.

1. Form Study Model: In the first phase, a model or form-study is provided in which the learner introduces their ambitions. The model is not meant for presentation but states ambitions in terms of geometry.

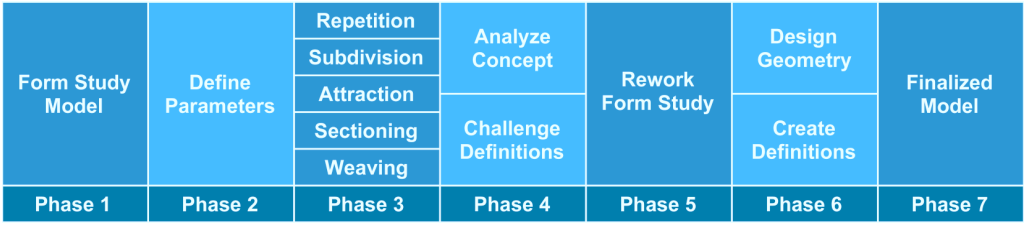


Figure 2
Preliminary Learning Situation Design for Model-Centred Parametric Design Education (PLMP)

2. Parameter Definition: In the second phase, the model is analyzed in conversation with mentors and peers. As a result of this analysis, definition and enumeration of parameters to be considered are highlighted.
3. Parametric Concepts: In the third phase, the parameters as highlighted in phase 2 are reflected to a selection of five parametric concepts (i.e. Repetition, Subdivision, Attraction, Sectioning, and Weaving) as used by Jabi (2013). Then, these concepts are discussed, altered, and extended when needed. Finally, one concept is chosen by each group of students for further review.
4. Concept Analysis: In the fourth phase, parametric concept as chosen in phase 3 is studied and reviewed. Firstly, a small report is made to introduce the concept theoretically. Next, existing codes and definitions are collected and applied to simple geometries resembling the intended model.
5. Rework Model: In the fifth phase, the parametric concepts are defined, and opportunities and challenges are explored. Next, the initial physical model or form study is reworked. The purpose of this model is like phase 1 (i.e. communication of the geometrical ambitions). However, in this phase, the ambitions are refined, and novel insights are introduced.
6. Parametric Design: In the sixth phase, a digital geometry is created based on the parametric concepts and ambitions as studied in phases 4 and 5.
7. Final Model: In the seventh phase, a presentation model is produced using the digital geometry of phase 6. This model is made using CAD-CAM technologies such as laser-cutting, 3D printing, or milling. When the step from phase 6 to 7 is not easily completed as the result of the complexity of the model used, phase 5 and 6 are repeated to introduce intermediate models.

To illustrate each phase of the PLMP, the course "Digital Culture and Generative Processes of Form" is used. During each phase learning outcome and research observation are introduced.

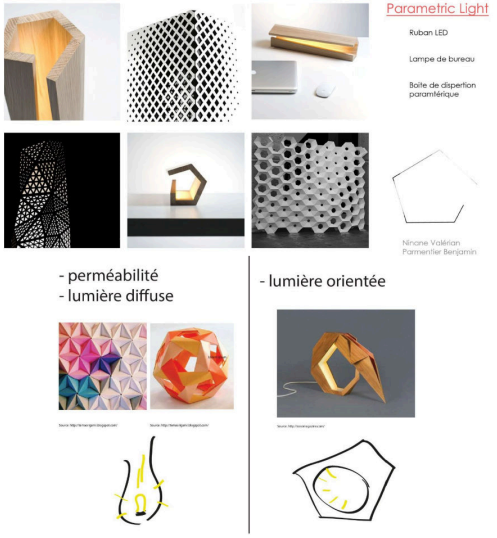


Figure 3
"Form Study Model", example of two groups' research and presentation of ambitions.

During the first phase (i.e. form study model), the students were requested to look for references and ideas for the lamp design through web research, form-study, and sketching (Figure 3). At this point in the curriculum, the students are comfortable with this process. Since the students have limited experience with the parametric concepts as used, the students are encouraged to explore subjective interests through loose constraints. During this phase, we experienced no significant bias related to their digital ability. Due to this lack of experience, the students show having a hard time explaining exactly what they want to achieve, which required some degree of flexibility in the process.

During the second phase (i.e. parameter definition), parametric software was practiced. As a result, the learner formed an understanding of various concepts involved in parametric design. Based on this understanding, the students' conceptual knowledge improved, which enabled them to define the parameters to consider in their research and design. As presented in Figure 4L, with the development of the students' experience, their parametric design intentions became more specific.

During the third phase (i.e. parametric concepts), the students are introduced to five of Jabi's "parametric concepts". Regardless of their previous research and design intentions, the students are requested to pick one of the concepts and refocus their work. To support this shift of focus and avoid a stressful situation, the tutors ensured that the students' design intentions were kept ambiguous during the previous phases. By framing their designs, the students was motivated to reconsider their ambitions and define subsequent steps.

During the fourth phase (i.e. concept analysis), based on the constraint as introduced in phase 3, references from previous phases are refined, and models are tested through existing codes and definitions (Figure 4L). Based on their improved conceptual knowledge, the students show a capacity to solve design problems that occur, and visibly connect the aspects as introduced in the previous phases (Figure 5).

During the fifth phase (i.e. rework model), a contained trial-and-error approach is introduced. As presented in Figure 4R, the chosen parametric concept has been studied and tested, and the students have acquired sufficient experience to improve their design through an iterative process of experience, disruption, and evaluation. At this stage, each group works at its own pace and produces as many design iterations as requested for the design.

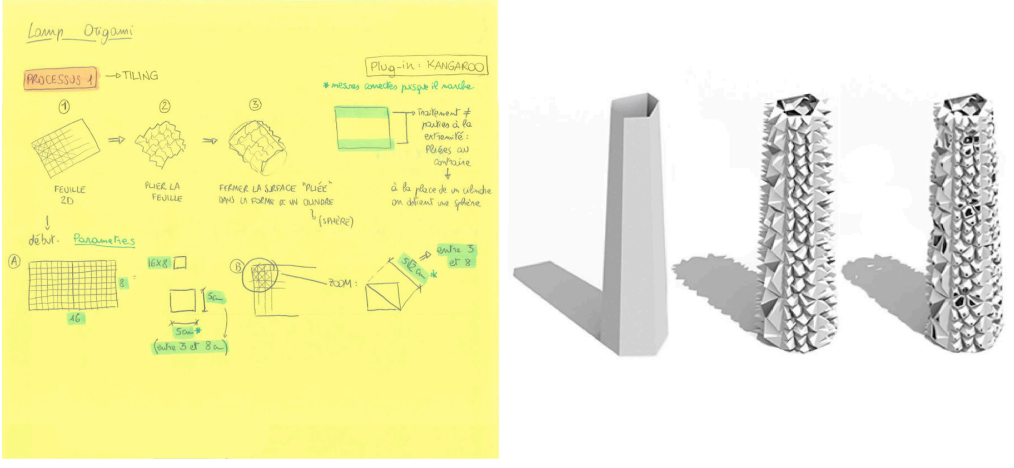


Figure 4
(L) "Parameter Definition", an example of a group of students starting to reflect on parameters. (R) Example of the "rework model" phase.

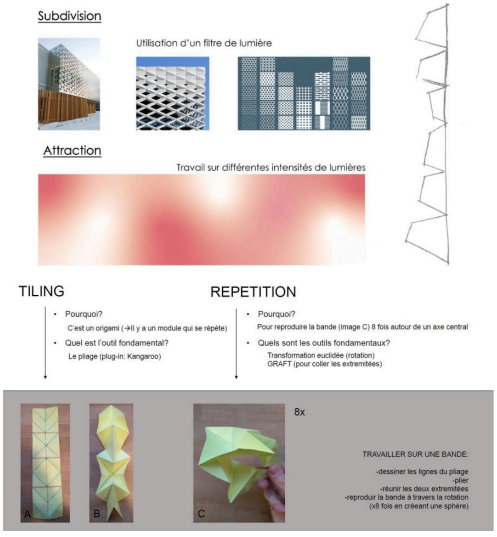


Figure 5
"Concept Analysis", Example of two groups refocusing their form research according to Jabi's concepts through testing and further research.

During the sixth phase (i.e. parametric design), the students reflect on the results of the previous phases and refine their model. As presented in Figure 6L, the final model must be described geometrically through each phase of the algorithm and show appropriate parametric flexibility.

For the seventh phase (i.e. final model), the students are requested to produce a physical output from the models as made during the sixth phase (Figure 6R). This phase serves to evaluate mainly two aspects. Firstly, the student is requested to present their control over the design as a whole, and secondly, the flexibility of the parametric model to adapt to the fabrication constraints. The latter is set by the tools and materials provided by the fablab the department partnered with for this project.

## CONCLUSIONS AND FUTURE PROSPECTS

Over the past decades, various scholars have indicated that the development of new digital design tools requires a new kind of knowledge. However, a review of scientific literature shows the confusion of vocabulary when defining this knowledge, and therefore the difficulty to construct a relevant and common pedagogical program. In that regard, this study presents a preliminary learning situation for parametric design within the framework of a master's course in architecture. The suggested and tested methodology is based on the notion of conceptual knowledge. In order to integrate this notion, the design process is structured into seven phases.

Considering the experience of the authors in giving this course through a two-direction teaching-learning method, this suggested learning situation design proved effective based on the following preliminary findings of. Firstly, by using form-study and physical models as a primary medium, both teacher and student could communicate effectively, without being restricted by digital challenges. Secondly, during each phase of the design process, the learner visibly improved regarding specificity and understanding of parametric conceptual involved. With each phase of the preliminary learning situation design, the student was able to converge specify their design ambitions more specifically. Finally, the successful production of the lamps shows that the sequencing allows the students a coherent design by understanding the concept.

The preliminary learning situation presented will evolve based on the feedback from this conference. For future work, we suggest a complementary approach that could be integrated in order to (un)confirm our preliminary results and thus assess the learning curve of students with a more quantitative method. In order to test the learning effectiveness of the PLMP, we refer to a study by John Hattie (2012). This study contains a set of meta-analyses of many research articles and ranks teaching-learning approaches based on effect size. In our case, we suggest using pre- post-testing using quizzes as a measurement instrument.

Figure 6
(L) Examples of phases of algorithm. (R) Some results of the "Final Model" phase, here as physical outputs.

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# Embodied Learning through Fabrication Aware Design

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*The contemporary culture of geometry-driven design stands as consequence of an institutionalised segregation between the fields of architecture, structure and construction. In turn, digital design methods that are both material and fabrication aware from the outset create space for uncertainty and the potential for embodied learning. Following this principle, this paper summarises the outcomes of a workshop developed to investigate the contribution of fabrication aware design methods in the production of a masonry block using both analogue and digital manufacturing. Students were to develop and investigate a design, through assembly techniques and configurations orientated around manual hot wire cutting, robotic tooling and three-dimensional printing. Outcomes were manufactured and compared regarding work precision, production time, material efficiency, cost and scalability. The analysis indicated that the most accurate results yielded from the robotic tooling system, and simultaneously exhibited the most efficient use of time, while the three-dimensional printer generated the least material waste, due to the nature of additive production. Fabrication aware design and comparative analysis enabled students to make more informed decisions while the use of rapid prototyping facilitated a relationship between digitalization and materiality allowing for a space in which uncertainty and reflection could be fostered. Reinforcing that fabrication aware design methods can unify the field and provide guidance to designers over multi-lateral aspects of a project.*

**Keywords:** *Fabrication-Aware Design, Rapid Prototyping, Embodiment*

## INTRODUCTION

The curriculum of architecture schools allocates the majority of its credits into design studio activities developed towards a predefined brief. The integration of digital tools into the early stages of design has been widely spread for the last 30 years. In turn, the illiterate inclusion of computers in the design stage is often criticised since it has resulted in a geometry-driven contemporary design culture (Oxman 2010). As an effect, materiality is typically conceptualised as a passive property assigned to a finalised geometry during later stages of design (Menges 2012). These outcomes are a result of a reductionist design practice as if it was a 'scientific problem' characterized by a high level of rationalisation and abstraction (Snod-

grass and Coyne 1997). Consequently, reducing the designer's agency in the system (Lyon 2005).

As an alternative, cognitive models focused on how the designer reflective practice can give back agency and enhance the learning experience as it facilitates an iterative process. Concepts as 'Structural Coupling' (Maturana and Varela 1980) and 'Reflection-in-action' (Schön 1983) support the idea of cognition and design as a situated (embodied) practice. Therefore, designer and object (sketches, models, prototypes) are in a dialogue. Schön (1983) argues that aspects of surprise, uncertainty and ambiguity overcome the immediate application of theory and technical knowledge. Both concepts were the main theoretical drivers of the workshop presented in the following. This paper proposes a 'fabrication-aware' activity combining materiality and manufacturing in the early stages of design as a way to enhance the student learning process. In this case, the use of rapid prototyping not only closes the loop between design and production but also enables reflection over physical objects that can inform the design decisions and vice-versa.

As an effect, this research investigates whether an exercise that benefits from a combination of digital tools and rapid prototyping enables cognitive aspects of structural coupling and 'reflection-in-action'. Moreover, what kind of framework and tools enhance this process and to what extent? Moreover, the paper reflects on the challenges and opportunities regarding the integration of a variety of digital manufacturing methods into the design curriculum.

This paper reviews the outcomes of a project-based learning exercise that introduces fabrication-aware-design as a methodology to reintroduce uncertainty and reinforce iterative processes. The proposed strategy teaches representation skills (3D modelling software) digital manufacturing and casting procedures for construction simultaneously, supported by the belief that materiality should inform decisions in the early stages of design. Thus, this framework overcomes the geometry-driven paradigm of contemporary architecture and sheds light to form and material integration.

## DESIGN AS AN EMBODIED AND REFLECTIVE PRACTICE

The design process addresses design 'problems', which are hard to define and do not dispose one definitive solution, also known as wicked and/or ill-defined problems (Rittel and Webber 1973). By definition, wicked problems diverge from scientific problems which require to be tested and verified; therefore, cannot be tackled from a research approach (Popper 1972). Snodgrass and Coyne (1997) support that design does not fall within the domain with a base in formal logic but belongs rather to the domain with a base in the processes of understanding and interpretation. The 'Autopoiesis' theory from (Maturana and Varela 1980) sheds light on aspects of the designer's subjectivity as the representation and interaction as essential parts for the cognitive process. Similarly, Schön (1983) advocates for 'embodied, tacit and process-based knowledge, rather than technical and rational approaches' (Herr 2009). Acknowledging Maturana, Varela (1980) and Schön (1983) principles, one can design exercises that stimulate uncertainty enhancing the learning process

### *Embodiment as Structural Coupling*

Supported by biological and phenomenological observation, Maturana and Varela (1980) brought into discussion aspects of the body structure and the individual perception as key elements for cognition (Lyon 2005). Additionally, the authors argue that these living systems are coupled with the environment in a way that both interfere with one other mutually. 'Structure coupling', also presented by the authors, "describes a process that occurs through repeated non-destructive perturbations between a system and its environment, each having an effect on the dynamical trajectory of the other" as summarised by Quick and Dautenhahn (1999). Cognition for them is understood as the result of this intricate relationship, therefore as an embodied and situated practice.

'Autopoiesis' and 'Structural Coupling' reframe it as a recursive, ongoing cyclical process. As the design process is a continuous learning (cognitive) process, in which the designer is unable to anticipate where each action will lead, one can understand that it is a fundamentally transformative process. Thus, the designer makes decisions based on the transformations, establishing a dialogue between process and object.

### *Reflective Practice*

Along these lines, Schön (1983) refers to design as 'reflection-in-action' which is 'a reflective conversation with the situation'. Design as 'reflection-in-action' is an interpretative activity, "a kaleidoscope of ever-changing reflections, revisions, false starts and backtracking" (Snodgrass and Coyne 1997). Therefore, he refutes the notion that design is as a straightforward transferable knowledge domain, in which technical and rational content will be taught and directly applied ('knowledge-to-action'). He argues that a designer starts their project with a vague idea and with the help of ambiguous representation 'tools' (as sketches), new insights are possible due to the designer's contextual interpretation. Reflection-in-action presupposes that the designer does not know the step-by-step to achieve their goal as a recipe (or algorithm), by the contrary, ther will learn through the process. Therefore, as Herr (2009) reaffirms "indeterminacy and ambiguity can be considered facilitators of new ways of seeing and thus of surprise and new insights". Therefore, the more a framework enables uncertainty and multiple interpretations, the more robust the design process becomes through the stimulation of a cognisant reflective process.

In response to the lack of interaction in a contemporary computational design environment, this paper proposes the use of physical models as tools to facilitate indeterminacy and ambiguity analogously to sketches in Schön's observations. Moreover, this review supports that rapid prototyping can enhance the 'Structural coupling' between 'designer - object' concurrently as reintegrating materiality into the early stages of design. The chosen manufacturing techniques range from low to high levels of automation, from manual cutting, three-dimensional printing to robotic wire cutting. Having a variety of methods enables the investigation, whether the level of abstraction of computational modelling is a barrier between the designer and the project. In parallel, students are also asked to assess their design facing quantitative efficiency parameters (cost, time, waste) to evaluate whether 'reflective-practice' and 'structural-coupling' enhance quantitative aspects as well as facilitating exploration throughout the design. The proposed exercise and its outcomes are presented as follows.

## MATERIALS AND METHODS

The two-week programmed workshop brief was presented to the students on the first day of the workshop, outlining the encompassed learning. This consisted of an initial training exercise on concrete casting, accompanied by direct tutorials on three-dimensional modelling software. Following this, the students then started their design proposal, prototyping and analysis with the students' main task being to design a traditional masonry brick (compression-only) produced via concrete based mix-casting. The rapid prototyping tools available included manual metal cutting, laser cutting, manual hot-wire cutting, robotic hot-wire cutting and three-dimensional printing.

### *Casting*

As a consequence of the students involved having limited or no previous experience of casting, the preliminary stage of the project encouraged the group to fulfil a casting procedure using a pre-established kit-of-parts from a previous masonry brick design (Figure 01). The casting stage included assembling the formwork, mixing and pouring the concrete. The goal for this learning-through-doing exercise was to gain insight into the requirements of their de-

sign and to determine potential manufacturing challenges and opportunities.

Figure 1
Casting with a kit-of-parts of a similar process.

### *Software Training and Early Design*

Concluding on a one-day tutorial covering the fundamental practice of Rhinoceros 3D, students worked over the following two days developing the design of a brick and its arrangements based on masonry principles (self-supported and compression-only structures). The brief defined the exclusive use of ruled surfaces for the brick design to accommodate the constraints of wire cutting. Meanwhile, secondary considerations around the design development orientated towards the overall consumption of material throughout the production of the mould, formwork, and resulting object. Having undertaken the initial construction exercises and supplementary training, the students could now engage with the design process whilst implementing a tangible response to fabrication through learned construction logics. The resulting design is illustrated in Figure 02 and was formed of a hallowed split-faced cuboid (210 x 165 x 165 mm), of which would feature an interior irregular-tapered void and a singular end condition that would consist of a split-faced, ruled-curve surface. To further optimize prototyping production, the brick size was coordinated to utilize the minimum dimension of the resourced materials (Styrofoam), measuring at 165 mm in depth. Tests regarding the brick's aggregation were also explored. One example is illustrated in Figure 03.

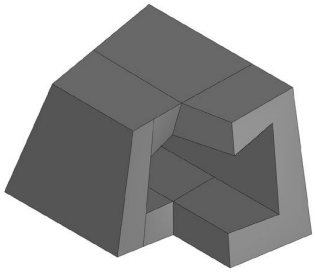
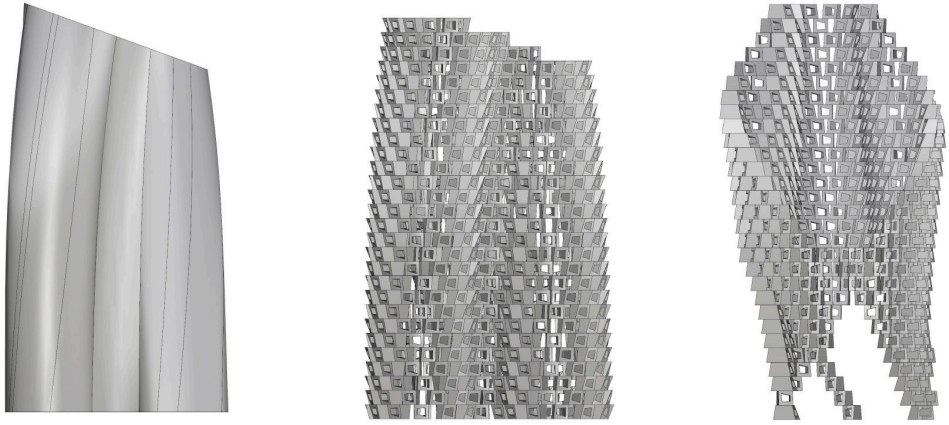


Figure 2
Brick initial design.

### *Prototyping*

Having defined the initial brick design, the students began inspecting the production methodology through the outlined manufacturing techniques, analysing their execution, and iterating their design approach were required to enhance the outcomes. The students were asked to develop their projects through three strands of production while examining their efficiency in working precision, production duration, material efficiency, associated cost and scalability. It is, however, important to disclaim that due to the limited timeframe, the students used the methods of manual and robotic cutting for the resulting pre-defined prototypical bricks instead of fulfilling the programmed variation of casting the final outcome. This enabled testing of the articulation, ag-

Figure 3
Assembly tests as part of the initial design test.

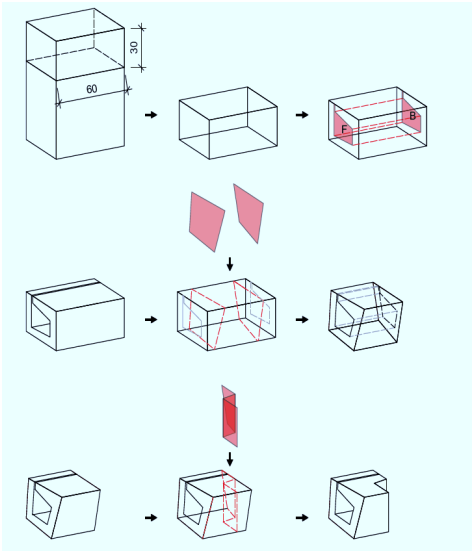


gregation and structural potential to scale and was deemed a satisfactory compromise against the learning outcomes of the program.

**Manual Hot-Wire Cutting.** In beginning the manual hot-wire cutting, students drew all the six external surfaces for laser cutting plywood templates used as cutting guides, chosen for its relatively low-cost and high strength. Once cut, the students began the manual hot-wire cutting following a two-step plan. Step One: Cut the length, width, height and central void using the front and rear template over the Styrofoam boards. Step Two: Place the remaining side templates over the foam and cut the negatives. The steps are illustrated in Figure 04. Upon use with the hot-wire cutter, the heat of the wire begun to sear the edge of the plywood template, removing the ability to use pressure to guide the wire, this contributed to a limited accuracy, causing disfiguration of the end product.

To mitigate this issue, the students coated the edge conditions of the front and rear guide surfaces with a strip of aluminium sheet, therefore allowing pressure to be applied without damage. Furthermore, the students replaced the side-mounted templates altogether, opting to use aluminium plates in an attempt to gain longevity for the process. Employing these methods of support, it accelerated the production of the foam variety and aided in increasing the accuracy of the cuts, although this could also be attributed to the increased skill of the user throughout the development.

Figure 4
Step by step manual cutting, template planes are highlighted in red.



**Robotic Hot-Wire Cutting.** Similar to the manual cutting, the robotic fabrication of bricks comprised of a subtractive method of cutting Styrofoam boards with hot-wire. Before cutting the bricks, the students worked across three stages. Stage One: File generation. Stage Two: Robotic setup. Stage Three: Material preparation. The programme for the robotic tool system was generated using Rhinoceros 3D, and the Robots plug-in inside of Grasshopper. For the robotic file, they specified the type of the robot (ABB 6620), the tool geometry, its centre point, and the targets. The targets then define the toolpath and cutting speed (8 mm/s) according to the material in use. Each face of the bricks outer geometry and the inner void are referred to as one cutting move, then subdivided into several actions describing the robots tool path.

At this stage, the students faced their first major challenge; the possibility of whilst cutting a portion of the brick, the cutting head could potentially collide with the materials supporting structure. Students first sliced the original foam boards (2400 x 600 x 165 mm) into smaller parts (300x200x165 mm) to optimise the material efficiency and to reduce the number of cuts/moves. Several cut orders and the tool's direction were tested to refine the tool's movement, the final order started cutting the front and the back faces, followed by the inner void and finally the brick's upper surface. The setup consisted of one foam board (support) and overhanging block (brick) to avoid the tool collision and wire-damage since the support was made of the same material as the brick. Students followed Health and Safety measures throughout, wearing specific protection masks and utilizing an industrial extraction system to mitigate the risk of fume inhalation from the materials off-gassing whilst being cut.

**Three-dimensional Printing.** The students used three-dimensional printing as a method to produce the mould negative. The negative was divided into two interlocking halves, creating a fully enclosed cast and reducing the number of parts involved. Figure 05 illustrates all the components required. In defining the formwork, the students acknowledged such conditions as structural efficiency, reducing support material, functional handling of the mould, and the print-heads directionality (reducing frictional surfaces). The three-dimensionally printed mould was comprised from a Filament Deposit Method (FDM) and each component took approximately six hours to print.

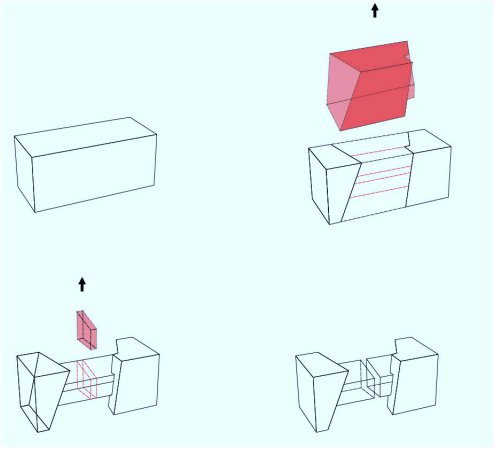


Figure 5
Casting print design composed of two interlockings sides to facilitate demoulding.

After making adaptions to the design in the digital modelling software, Rhinoceros 3D, the students exported the geometry and began to define the printer settings using Ultimaker Cura. This manufacturing method requires very limited set-up and the final output (printing) is generated automatically. Once printed, the students finalized the process by removing the internal (structural) supports and setting the outer laser cut box for the casting as seen in Figure 05.

## *Analysis*

Critical to the project's success, the students were required to analyse the embedded logics and values of the manufacturing processes and appraise their outcomes through criteria of efficiency and functionality. These criteria were introduced to propagate their awareness and reflection, becoming inter-

spersed into their design consideration. The criteria encompassed working precision (mm), production time (minute, hour), material efficiency (waste %) and cost/scalability (£per). For each methodology, an indication marker was given referencing the potential of each process against the outlined criterion. The marking had five standings; highly efficient (4), efficient (3), average (2), inefficient (1), very inefficient (0). Table 01 summaries the score's benchmarks for each criterion.

Table 1
Benchmark criteria.

| | 4 | 3 | 2 | 1 | 0 |
|---|---|---|---|---|---|
| Work Precision (mm) | <1 | 1 | 2 | 3 | 4 |
| Production Time (£) | <1 | 1 | 2 | 3 | 4 |
| Material Efficiency (%) | <5 | 10 | 15 | 20 | 25 |
| Cost – set-up (£) | <5 | 5 | 10 | 20 | 40 |
| Cost – unit (£) | <0,5 | 0,5 | 1 | 2 | 4 |

## RESULTS

Each production method undertook an evaluation referencing the listed criteria as well as its ability to sustain reflection and interaction through the design process. The results are discussed and compared using a mark-based system, summarised in Table 02.

Table 2
Prototyping method comparison.

| | Manual | Robotic | 3D Pr |
|---|---|---|---|
| Working Precision | 4 | 2 | 1 |
| Production Time | 1 | 2 | 4 |
| Material Efficiency | 2 | 3 | 4 |
| Cost/ Scalability | 1 | 3 | 4 |
| Design interaction | 3 | 1 | 3 |

**Manual Hot-Wire Cutting.** In the initial stages of the production stage, the students identified that the manual hot-wire cutting generated the least efficient working precision due to the operator's lack of steadiness, having a varied degree of accuracy (mm) but a resulted in an approximate material loss of up to 5%. As the students were able to start production immediately once the templates were complete, with little practical set-up, this aided to reduce production time. However, the prolonged time to learn to manually operate and pre-process the material resulted in an overall increased production time, with initial preparation time, including template and guide cutting of around 2 hours, followed by each block taking around 10 minutes to produce thereafter. Although the aluminium guides increased control over the guidance of cutting, components marginally varied in size and compromised the finished precision, while producing an increased yield of waste material, through small debris and negative off-cuts, overall producing around 25% waste. The relatively low cost of this method, £10 for templates and £2 for the Styrofoam brick per brick, needs to be weighed against the longevity of the mould, as although this process has a high production yield the properties of the foam mould have a low durability tolerance, therefore inflating the overall cost at scale due to replacements being required within a significantly reduced timespan.

**Robotic Hot-Wire Cutting.** Robotic wire-cutting displayed the highest precision performance, producing a constant sizing with a high degree of finished precision, primarily due to the robotic cutting settings, allowing for the cutting speed and space between surface cuts to be maintained at a consistent level in comparison to the manual iterations. The kerf of the wire leaves around 2mm of material removal (approximately 1mm either side of the movement) and should be a consideration of sizing beforehand. The production of this methods timescale was elongated due to its complexity in prefabrication set-up, taking around 21 hours. In turn, however, once the robotic programming file was set and the material in place, the production speed increased, and students were able to cut one foam brick in approximately 5 minutes. Elevating the material efficiency in comparison to the manual cutting, although it is worth noting that this method also resulted in a large number of offcuts, around 20% with little function for further use. Although the robotic tool system has an initial lower cost, approximately £10 for the set-up and £1,60 for the Styrofoam brick per brick, the process is

machinery-dependent for repetitive production and the moulds would be easily susceptible to decay and damage reducing the efficiency of cost in-line with the lifespan of the mould. An example of the prototypical brick is displayed in Figure 06.

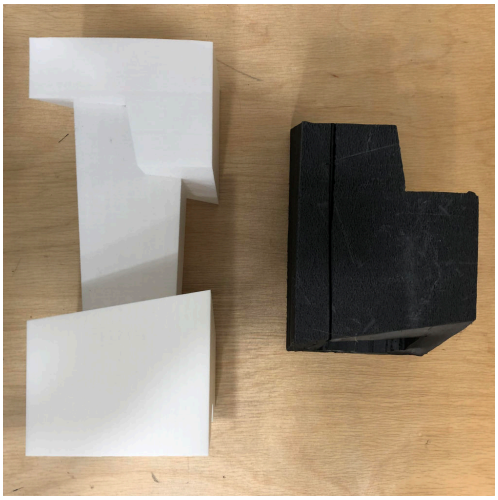


Figure 6
3D printed mould and hot-wire cut prototypical brick.

**3D Printing.** The findings indicated that the method of three-dimensional printing produced a high degree of working precision, due to a working tolerance of 0.4mm for precision. As a result of the increased precision and method of material placement, the production time of this technique is considerably heightened, around six hours per print, in comparison with the manual procedures. Although due to its addictive nature, there is next to no waste for this production approach, with exception to that of the additional 'support' material used as a 'scaffolding' for the object. For both of the two printed halves, the support material sums up to an amount of 15% of the total material. This aspect is geometry dependent and could be reduced to zero through the design. The scalability and cost of this method is the trade-off between an increased timespan of production and its highly durable outcome that has an increased longevity of use. Therefore, although it does take longer to print the mould, this is outweighed by reducing the overall cost of £15 for the mould and £0,40 for the concrete mix per brick. An example of the print is shown on the left side of Figure 06.

**Representation and Refflection.** Both manual cutting and three-dimensional printing enabled changes in the design since students engaged with the physical models immediately. In turn, the robotic cutting required a longer setup and a custom file, therefore, required the need for third-party support. This, in fact, acted as a barrier between the students and the physical object. Whilst in the process of manual cutting, students also altered the manufacturing process by adding aluminium sheets to the template guides, which demonstrated their reflection over the 'live' situation. Although three-dimensional printing requires a finalized file to print, users can rapidly produce prototypes for analysis and adjustment. After reviewing their initial prototype, the students concluded that the structural thickness could be reduced by two-thirds while still maintaining an adequate proportional strength, in-turn reducing print time and material usage by 50%.

## CONCLUSION

### *Project Outcomes and Limitations*

In evaluating the project, the students found the Robotic tool system the most efficient method as it produced both moderately accurate and time-efficient outcomes with a low associated cost despite an elongated setup period. In comparison to both the manual procedure of cutting and three-dimensional printing, it offered the most scalable approach to mass production with its only considerable limitation being that of a decreased overall lifespan.

In conducting a project review with the student group, we found that the outcome of the project had been successful, allowing the students to realise a project from conception through to effectively producing a viable outcome. Students highlighted the challenge of producing finished casts for each manufacturing method within the allotted period of time. While this was accredited to a high degree of exper-

imentation within each method to achieve an optimized outcome. The final bricks cut with manual and robotic wire-cut are illustrated in Figure 07.

Figure 7
Final assembly of bricks.

### *Learning Experinece*

Using a short-term project at the beginning of the academic year, students can be introduced to a series of fundamental processes building an early understanding of fabrication methods for deployment later within their studies. By orientating the project around the production of a design outcome across several means of production, the students interrogate the function of each method embedding materially into the design process. This awards the students the opportunity for reflection-on-action (retrospective) at the initial stages of their learning experience for utilisation throughout their studies.

Furthermore, focusing the project around production and evaluation, the exercise provides the opportunity for expansion of inherited knowledge and refined outcomes. In other words, the use of physical models did contribute to reflection-in-action enlarging indeterminacy and surprise based on a situated practice. First, the initial casting helped students to understand the process through experience and informed them about the method constrains. Methods with little set-up or simple manufacturing files, as the manual cutting and 3D printing, facilitated this even further whereas new insights emerged from the design-object dialogue. The changes made to the design of the three-dimensional printing mould formed a critical juncture in the student's understanding of how fabrication informs design outcomes. In turn, methods requiring customised settings such as robotic tooling reduced the level of interaction with the physical prototype due to the high level of information required in the set-up.

Although the presented results are constrained to a short exercise, it is possible to draw some pathways for future implementation of digital manufacturing in the curriculum. According to both quantitative and qualitative results, reduced time techniques such as manual cutting and three-dimensional printing enable a higher level of iterations in the design process effortlessly. Therefore, these methods are easy to integrate independently to the student background and in any stage of the design process. On the other hand, integrating robotic manufacturing as part of the learning environment yet poses challenges due to the required programming knowledge. Exercises focused on developing applied skills to program the robot as well as to understand materiality can be possible attempt to minimise the barrier caused by the long set-up. As indicated, a multidisciplinary research project envisioning the subject should consider that every method, to different degrees, tends to open space for ambiguity and contextual interpretation. Therefore, physicals models produced using cutting edge digital manufacturing should be explored as much as sketches in the designer's representation toolbox.

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# A Novel Crowdsourcing-based Approach for Collaborative Architectural Design

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*This paper provides an overview of ``Architasker'', a large-scale crowdsourcing approach, platform, and method that enables a collaborative professional architectural design process in collaboration with a community of stakeholders. The platform includes communicating complex architectural project requirements; solution space exploration using different micro-tasks like sketching, 2D and 3D CAD; design selection; and design review as an evolutionary process. The architectural crowdsourcing model underlying the platform is contextualized in the state-of-the-art research on creative crowdsourcing methods and is supported by relevant evidence from empirical experiments. Experimental results validate the effectiveness of the method to generate architectural artifacts by harnessing the skills, talents, and experience of architects and the opinions and values of the stakeholders.*

**Keywords:** *Crowdsourcing, Participatory Design, Human Computation, Creative Crowdsourcing, Co-Design, Collective Intelligence*

## INTRODUCTION

Recent advances in information technologies have led to the emergence of new collaborative design methods. One such method is crowdsourcing, an Internet-based method that allows specified crowds to collaborate on producing information products.

The term "crowdsourcing" was coined to refer to a production method where traditional work performed by an employee was outsourced to a large and undefined group of people. Since then, the term has acquired many and varied uses. For instance, crowdsourcing can refer to the recently emerging Internet phenomenon where different websites use their audiences to generate new knowledge or to the practice of publishing an 'open call' to receive information proposals from the public. Crowdsourcing unfolds in the following three steps: (1) disassembling a complex cognitive task into several micro-tasks; (2) using collective intelligence to solve those micro-tasks; and (3) reassembling the solutions.

Since architecture is an information industry (Porat 1977), information technologies have a strong potential in collaborative architectural design as an open-source, transparent, community-engaging design process (Ratti and Claudel 2015; Dortheimer and Margalit 2020).

However, despite the advantages of crowdsourcing-such as the possibility to reach, re-

cruit and engage a vast and worldwide pool of human intelligence (Milo 2011) or cost-effectiveness due precise budget allocation and organization of work in micro-tasks (Milo 2011), available crowdsourcing methods (e.g., Wu et al. 2015; Retelny et al. 2014; Valentine et al. 2017) remain somewhat limited in coping with architectural design challenges (see Table 1). Specifically, available methods fall short of integrating the input of various members in the design product and in facilitating this input in the course of the design process, rather than at its end.

### *Architecture Competitions*

Crowdsourcing is not fundamentally new to architectural design (Angelico and As 2012). In fact, public contests, which are similar to crowdsourcing in that they are based on an "open-call" to an undefined crowd, have long been a common and accepted practice used to generate and evaluate innovative design solutions. Overall, architectural competitions are an essential part of the training of architects in higher education institutions (Guilherme, 2014). Given that competitions are part of the architect's tradition, several architectural crowdsourcing websites offer their clients arranging online architecture competitions have emerged. However, while the competition model is a valuable innovation approach in architecture, it does not facilitate the collaboration of various stakeholders in the design process. Except for defining the requirements and selecting the winner, the owner and other stakeholders are not directly involved in the design process. In addition, since most of the competition participants are not compensated for their efforts, this approach raises several ethical issues (Deamer 2015; Keslacy 2018). In this context, there is an urgent need to investigate the potential of crowdsourcing methods in architectural design.

In the present study, we experimented with an online collaborative software that is similar to Virtual Design Studio (VDS), a software that supports communication, organization, and presentation of designs (Maher and Simoff 1999; Chiu 2002) and offers a flexible creative virtual environment for design and critique (Lotz et al. 2019). Our approach adapts representation ideas from VDS, but more importantly, distributes the creative process using micro-tasks and enforces a specific workflow.

### *Research Approach*

Our aim was to develop a creative architectural crowdsourcing model based on stand-alone micro-tasks and assembling their output into a larger product. Since micro-tasks are limited in their scope, the crowdsourcing process requires both the designs of multiple architects and the design preferences and feedback of stakeholders.

The main research question addressed in this study was as follows: *What types of crowdsourcing strategies and workflows can improve the integration of multiple architects and stakeholders during the design process?*

To address this question, based on the results of a review of relevant literature in the field of creative crowdsourcing, we first constructed a preliminary crowdsourcing model. Then, the model was applied as a web-based software, tested and developed in two experimental workshops delivered over two semesters. A total of 25 architecture students from the 2nd to the 5th years of study and eight experienced architects recruited through the Upwork freelance platform participated in the study.

The students were rewarded with one academic point for their participation over the semester; the freelance architects were paid between 7 and 10 USD per hour. Each lesson included 2-3 experiments and a survey to capture the participants' feelings and opinions. The data, including the generated artifacts, rating, review, survey answers, were stored in a database for further analysis and comparison. The quality of the produced artifacts was evaluated by three expert architects. Based on the results of this analysis, the initial model was updated. Finally, the updated model was also experimentally tested (see Figure 1).

Table 1
Comparison of creative design and creative crowdsourcing methods

| Property | Architasker | Yu and Nickerson 2011 | Sun et al. 2015 | Wu et al. 2015 | Retelny et al. 2014 | Arcbazar / GoPillar |
|---|---|---|---|---|---|---|
| Platform kind | Experimental | Experimental | Experimental | Experimental | Experimental | Commercial |
| Creative principle | Medium changing iterations | Genetic algorithm | Idea trees | Tournament like ratings | Ad-hoc teams | One or two stage competition |
| Deliverable | Architecture and interior-design | Chair | Recreation facility | Room layout | Digital products | Architecture and interior-design |
| Crowd kind | Freelancers and stakeholders | Mechanical Turk | Freelancers | Mechanical Turk | Freelancers | Contestants |
| Crowd size | 33 | 1047 | 23 | Hundreds | 22 | Dozens |
| Evaluation method | Selection | Rating | Idea tree | Rating | - | Rating |
| Tools | Napkin Sketch, Professional software | Google drawing | SketchFans (custom application) | Google drawing | Napkin Sketch, Professional software | Professional software |
| Task kind | Micro-tasks | Micro-tasks | Micro-tasks | Micro-tasks | Project tasks | Competition |
| Stakeholders participation | At each iteration | - | - | - | At the end | At the end of each stage |
| Segmentation | Yes | Yes | Yes | Yes | Yes | No |

The remainder of the paper is organized as follows. First, we review several previous studies of creative crowdsourcing. Next, we present our crowdsourcing model by describing the protocol objects, micro-task blocks, and the creative process. Then, we present the some results and discuss issues that have emerged during the experiments and affected our model. Finally, the results are summarized, and conclusions are drawn.

## *Creative Crowdsourcing*

This section reviews several crowdsourcing systems and previous studies that aimed to capture human creativity in creative and complex tasks, such as graphic design, software development, article writing, and so forth. As will be discussed in this section, each relevant method attempts to implement a different mode of operation and has its own strengths and limitations. Our work integrates the essential ideas from these methods into a crowd-based architecture design process.

Until now, available crowdsourcing systems have applied different approaches to split complex tasks into micro-tasks and to merge the output of those multiple micro-tasks into a larger product. One of the relevant approaches is to create micro-tasks based on a dependency graph algorithm that spouts new tasks based on the completion of other tasks, thereby enhancing the effectiveness of the workflow (Kulkarni et al. 2011; Kittur et al. 2011). Different approaches are based on a genetic-like algorithm where more creative designs are generated (Yu and Nickerson 2011). However, our creative process is based on tree logic, having artifacts as branches and new designs as leaves (Sun et al. 2015).

An essential part of creative crowdsourcing approaches is the way to select the most desirable outcomes. In this respect, most methods select tasks by performing an evaluation task where the participants rate the designs on a scale (Kittur et al. 2011; Yu and Nickerson 2011; Wu et al. 2015). Therefore, this approach is similar to the one employed in the traditional competition model .

Overall, architecture is described using a graphic representation. Previous research has used digital sketching tools to generate design ideas using various web-based tools, including an iPad touch-based application (Sun et al. 2015), mouse sketching (Yu

and Nickerson 2011; Wu et al. 2014), or parametric design (Fisher-Gewirtzman and Polak 2017). However, in the present study, along with offline traditional design methods like napkin sketches (Goldschmidt 1991; Shah et al. 2001), we also applied offline digital tools like SketchUp models and AutoCAD drawings shared and presented using Autodesk's cloud platform A360.

Finally, to collect the review data from stakeholders and architects, we assumed that the feedback given to study participants improves the quality of generated solutions (Wooten and Ulrich 2017, Luther et al. 2015; Greenberg et al. 2015).

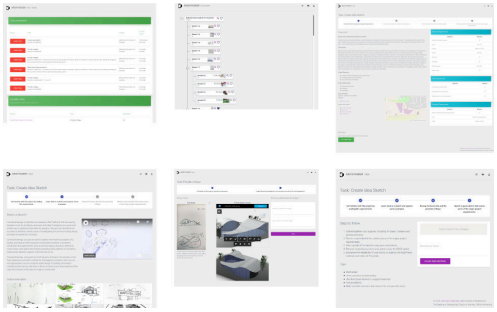

Figure 1
Architasker screens: Task list, Artifact tree, Brief, Example, Review and Steps

## CROWDSOURCING MODEL

This section describes our refined crowdsourcing model on three levels. First, we present the protocol objects: the brief object and the artifacts objects. This is followed by the discussion of the "Design-Select-Review blocks" (DSR blocks), which represent design iteration in the creative process and are identified by the specific artifact they generate. The blocks have artifact and brief used as a protocol between the tasks. Finally, we describe the creative process based on the DSR blocks.

### *Protocol Objects*

The information transferred between micro-tasks is defined by the following two types of objects: (1) the brief object and (2) the artifact objects.

The brief object is a data structure loosely based on RIBA's plan of work (RIBA 2013). Since an architectural project brief might span hundreds of pages, which makes it impractical to use it for micro-tasks that are only several hours long, the brief object is a summary of a standard brief and includes the project name, desired outcomes, client profile, project objectives, project stakeholders, and links to various resources such as Wikipedia pages, Google Earth, or photos of the area and precedents. The brief also includes essential site information, such as site CAD model, which includes the plot and surroundings to provide a better understanding of the existing spatial settings.

The artifact objects, which are generated in design micro-tasks, later become inputs for the next micro-tasks that build upon them. Artifacts, which hold a reference to traditional architectural artifacts by having graphic or CAD files, contain textual descriptions and review information to facilitate the improvement process. Our system includes the following artifacts: concept sketches, architectural sketches, 2D CAD drawings, and 3D CAD models. Therefore, our system is similar to the commercial architectural crowdsourcing systems and differs from most research-based systems that use exclusively online tools.

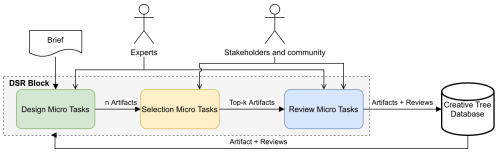


Figure 2
The DSR block process and actors diagram

### *DSR Blocks*

The DSR blocks are small design competitions performed by multiple participants (see Figure 2). Each block consists of the following three types of tasks: (1) design tasks to explore the design space; (2) selection tasks aiming to identify the most suitable artifacts; and (3) review tasks aiming to provide valuable feedback for later iterations. Every block is performed in synchronous iterations, so that all micro-tasks of one type must be completed before start-

ing on the next type of micro-tasks. Any micro-task should be independent of other tasks other than the performance order set in the creative process. Micro-tasks are designed in a way so that they can be performed with random participants. New tasks are assigned automatically to selected participants once all active tasks are concluded. The selection of the participants is performed by the project manager.

**Design micro-task.** The goal of design micro-tasks is to generate a new artifact using a limited-time design charrette. The input for these tasks is a brief and an optional base-artifact that includes reviews.

A design micro-task consists of the following screens: (1) a brief overview screen showing all requirements and information; (2) a task overview screen that includes a video demonstrating the task and example outputs; (3) an optional base-artifact screen showing an artifact to improve, along with all collected feedback and files to download; (4) a task-steps screen that provides technical steps to complete the task, e.g., how to crop and enhance photographs of sketches, or how to upload CAD models.

**Selection micro-task.** The goal of selection micro-tasks is to provide a rating that is then used to filter the artifacts obtained from numerous design micro-tasks to select the most suitable designs for further improvement. An array of artifacts is obtained as input, and the filtered array includes at least one artifact. This is achieved by collecting the selections of multiple participants and combining them using a predefined threshold.

Selection micro-tasks consist of the brief overview screen and the selection screen that displays all artifacts produced in the last design iteration, and only one artifact can be selected in each micro-task.

**Review micro-task.** Review micro-tasks involve requesting from the participants various types of review data, such as design critique, and improvement ideas. In a micro-task, the brief and one artifact are received as input, while the output is an artifact with added information.

The task consists of the following two screens: (1) the brief overview screen; and (2) a review screen showing an artifact to be reviewed, the artifact it is based on, and an input area. The input area collects information via open-ended questions for qualitative critique. For qualitative feedback, the participants have to respond to the following questions: "What do you like about the design?" and "How would you improve the design?"

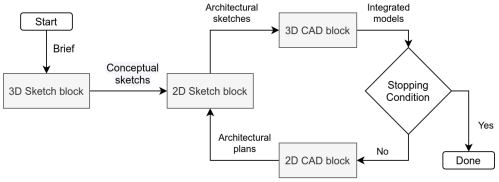


Figure 3
Creative process diagram

## *Creative Process*

The crowdsourcing process starts with the creation of a brief specified by the project manager (see Figure 3). Next, the first DSR block generates conceptual sketches provided to an iterative improvement process. The sketches are then explored using an architectural sketching block that generates plans, elevations, and sections. In the next block, the selected architectural artifacts are merged into 3D CAD models. The selected 3D models are detailed to 2D CAD plans, sections, and elevations in the following block. The resulting 2D CAD drawings are provided again to the architectural sketching block for another improvement iteration (see Figure 4).

After 3D Model-Integration, there is a stopping-condition, since this is the only point where a monovalent artifact provides a full picture of the design.

**3D sketch DSR block - Concept.** The aim of the first stage is to explore the design space and generate multiple design proposals that solve the high-level requirements. This is achieved by sketching micro-tasks that require a 3D presentation of an architectural idea. Finally, the most suitable sketches are selected, and review information is added using the selection and review micro-tasks that are a part of the block.

**2D sketch DSR block - Architectural.** Concept sketches provide limited architectural information. Accordingly, sketching micro-tasks are used to generate plans, sections, and elevation sketches from a concept artifact via adding more vital information. In later iterations, along with concept sketches, this block also receives 2D CAD drawings to facilitate abstract problem solving using sketching. Again, the most valuable artifacts are selected, and review information is provided using selection and review micro-tasks.

**3D Model-Integration DSR block.** Upon generation of multiple architectural artifacts, this block merges them into 3D CAD models. This design task requires the architects to choose a conceptual artifact, collect the relevant architectural artifacts, and generate a 3D model using the SketchUp software. The precise nature of the CAD model requires the architect to solve spatial issues that did not exist in the 2D sketch, which adds more information. Upon completion of all tasks, the artifacts are selected using selection micro-tasks, reviewed, and valuable feedback for further improvement is provided.

**2D CAD DSR block - Division.** The 2D Division DSR block generates 2D CAD drawings, such as plans, sections, and elevations from the model. Technically, this is performed via first creating "2D planes" and then exporting them from the SketchUp software to AutoCad (a 2D drawing software). The drawings are detailed by adding furniture, doors, windows, and materials that meet predefined technical instructions. The finished drawings are filtered by a selection micro-task and undergo review for further issues that arise from the drawings. Finally, the selected artifacts are provided as input for the architectural sketch task for further improvement and detailing of the design.

**Stopping condition.** On reaching the maximum defined number of iterations or upon a project manager decision, the design process stops. As mentioned previously, this occurs only after the 3D CAD block, an information-rich 3D model, is created. The decision is based on the manager's judgment that takes into account the generated artifacts design fitness, quality, budget, and time constraints.

## RESULTS

The crowdsourcing model was tested in 26 experiments. A total of 232 architectural artifacts were generated using the design task. 5671 ratings and selections were generated using the selection task. 3164 reviews were generated by the review task. Furthermore, a total of 552 survey responses were collected.

The crowdsourcing method successfully produced multiple architectural designs. The designs evolved over time through different architectural media and using different tools. The concept of organizing the micro-tasks in DSR blocks proved to be beneficial, since it helped to cope with the complexity and multiplicity of the creative process.

### *Design Task*

The results showed that compared to the CAD software, sketching was beneficial for the generation of quick conceptual designs. In addition, several experiments were conducted to improve CAD artifacts.

Figure 4
An example of the different DSR block output artifacts generated in an experiment to design a detached house

Using CAD software, the participants demonstrated poor performance in improving the design comparison to sketching. Moreover, the design quality deteriorated over time. However, when the participants were asked to use sketching to improve various CAD files, better performance was observed.

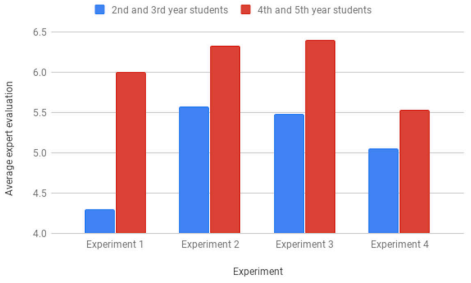


Figure 5
Average expert rating gap between the 2nd-3rd year students vs. 4th-5th year students across four experiments

As can be seen in Figure 5, more experienced participants (i.e., 4th and 5th students) demonstrated better design performance and received 15% higher expert ratings on average. In addition, the artifacts generated by more experienced architects were selected more frequently.

### *Selection Task*

Selecting the best design ideas is a challenging task, thus we tried to create a method of measuring good architectural design using a well-structured micro-task.

We experimented with some artifact rating micro-tasks using different rating criteria. Then, following Wu et al. (2015), the results were compared to expert ratings. The results showed that, while there was a high correlation between expert and non-experts ratings, in many cases, the most promising designs were in the second or third places, with a minimal difference from the highest score (see Figure 6).

Instead of providing a rating score for each artifact, we asked the participants to select the best artifact from a list. Due to providing the participants with an overview of all artifacts, the selection became easier, and a clear identification of the best artifact was possible (see Figure 6).

In this study, the design task experiments were conducted with students of 2th-5th years of study; the work was also evaluated by both expert architects and non-architects. The results of comparing the ratings showed a correlation between expert and non-expert average ratings and student ratings $(r^2 = 0.64)$ (see Figure 7).

It is important to note that when designers participate in the selection tasks, we noted bias issues. Some designers selected their own designed artifacts and rated them higher in contrast to the expert evaluation and the evaluation of the rest of the participants.

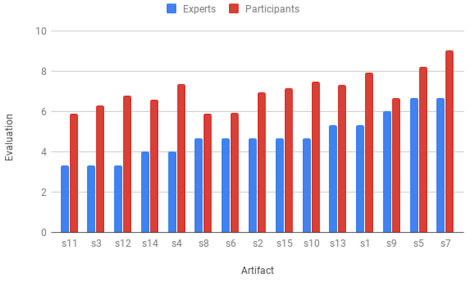


Figure 7
Relation between experts and participants' average ratings shown similar evaluations.

### *Review Task*

In experimenting with review tasks, we evaluated the quality of reviews and examined whether the designers addressed the issues in the next design task. The results showed that a review task requires sufficient time in order to be able to provide useful review data. Limiting the number of questions generated more detailed reviews. Also, reviewing all generated artifacts before the selection task was wasteful, since most of the artifacts were discarded.

The analysis of the review data did not highlight considerable differences between reviews provided by more and less senior students.

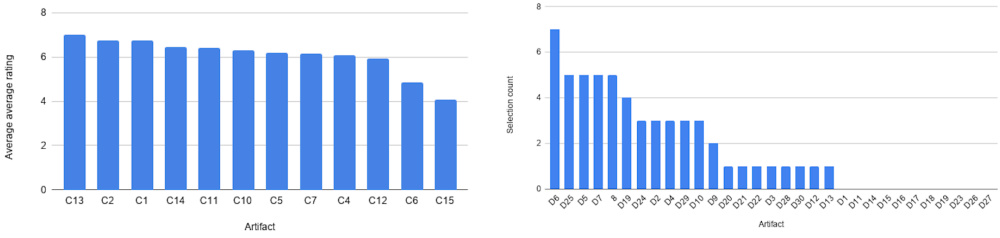


Figure 6
A comparison between artifact rating (left panel) and artifact selection (right panel) tasks. Due to minor differences, it was not clear from the rating output which was the preferred artifact (left panel). However, the selection task provided a clear overview on the preferred artifacts (right panel).

## DISCUSSION

In the present study, we experimented with the crowdsourcing software to evaluate the effectiveness, quality, and efficiency of the tested model. This section discusses some questions that have emerged during the experiments and affected the refined model presented in the previous sections.

### *Sketching*

According to our results, sketching proved to be a fast and effective way to express design ideas, plans, sections, and elevations. Specifically, it has proven to be not only beneficial for ideation, but also capable of facilitating problem solving.

While sketching is known to be a valuable design-thinking tool (Goldschmidt 1991), design crowdsourcing research has been more focused on digital tools (Yu and Nickerson 2011; Sun et al. 2015; Wu et al. 2015). Based on our results, we argue that sketching is a valuable tool that can be meaningfully used in design crowdsourcing and digital workflows.

### *Artifact Selection*

The observed high correlation between the average ratings of non-experts and experts suggests that stakeholders' opinions about artifacts may be similar to those of architecture experts.

We also observed that it was beneficial to allow parallel development of multiple ideas, as this involved multiple branches in the design process and added fuzziness and tolerance in the selection of the most suitable artifacts (see also Sun et al. 2015). However, a limitation of this approach is that it may be time-consuming and not sufficiently cost-effective: that is, time and money could be invested in the ideas that will be later discarded. Notwithstanding, the advantages of this approach are that, first, it allows competition between ideas that facilitate better design and, second, it reassures stakeholders and designers that decisions are made democratically, and that multiple opinions are allowed.

Furthermore, in order to identify the best designs, we allowed the designers to choose the artifact they wanted to develop. Following Sun et al. (2015), we assumed that the best designs would be selected by the highest number of designers. This approach was proven successful, and the designer selection was similar to expert evaluation and the selection task outcome. However, there could a bias when some designers decide to keep their low-quality artifact. Therefore, this method cannot replace a selection task and should follow it to allow designers to select the artifact they prefer.

### *Quality Considerations*

Quality is achieved through the multiplicity of design tasks and produced artifacts. The selection process highlights the best designs, ensuring that high quality is achieved. However, there are several considerations regarding the quality of the artifacts.

The results of the first experiment demonstrated that providing a brief right before the sketching task was stressful for the participants, resulting in low-quality artifacts. After providing the brief a day before the task, the participants performed better and more effectively focused on the design. Based

on these results, we can conclude that, in creative crowdsourcing tasks, additional time should be provided to the designers to "sleep over it" before they start expressing the design.

The survey results also showed that the participants enjoyed using the software, creating designs and getting satisfaction from the competition. Therefore, the competition promoted achievement of better results (i.e., higher-quality artifacts); a positive trend between the following experiment artifact evaluations is shown in Figure 5.

### *Participatory Design*

This paper aimed to identify crowdsourcing methods that would help integrate designers and stakeholders into a creative process. The proposed process consisted of design, selection, and review micro-tasks. We experimentally determined in which tasks non-expert stakeholders and community members can participate.

Design micro-tasks should be performed by architects, since architectural design skill that takes considerable time to learn (Dortheimer and Margalit 2020). Architects know how to solve complex requirements, generate quality sketches and operate CAD software. However, although non-architects may lack the skills to express an idea using sketching, and most non-experts do not have the knowledge of the CAD software, this does not mean that all non-architects cannot participate. However, if they participate, in all likelihood, they will underperform, and their artifacts will be discarded. In our results, we observed a strong correlation between design experience and artifact quality evaluation (see Figure 5).

Since selecting specific designs does not necessarily require a priori knowledge or skills, the selection of most suitable artifacts may be performed by non-experts. This conclusion is based on the experiment results (see Figure 7) on the correlation between non-expert and expert evaluations. While professional architects may have a broader understanding of the quality of a design, in the present study, we reasoned that owing to a better knowledge of the project's environment, culture, and context, non-expert stakeholders' input is as significant as that of experts. However, allowing the designers to select their desired artifact might be biased and should thus be discouraged.

Similarly to the selection micro-task, the review micro-tasks can be performed by both experts and non-experts.

### *Limitations and Future Research*

The present study has several limitations. First, while we experimented with a group of participants (N=33) that was sufficient for our experiments, but this does not constitute as a "crowd". We suggest that future research will experiment with a group of hundreds participants acting as stakeholders to learn more about the selection and review tasks. Second, our results are based on experiments with architecture students with one to four years of experience, acting as stakeholders with a simulated project and not real stakeholders. Further research with a real-life urban project and communities could test the software and model on a larger scale. It would also be highlight important issues related to socio-demographic inequality in crowdsourced civic participation.

## CONCLUSIONS

This study presented a large-scale crowdsourcing model and platform based on the evidence from 26 experiments. The presented model successfully generated artifacts by engaging architects and stakeholders in the creative process by harnessing the architects' creativity and skill, on the one hand, and the stakeholders' viewpoints, on the other hand. Therefore, the process successfully integrated the various stakeholders in the course of the design process, rather at its end.

We used the DSR blocks as a framework for creative crowdsourcing. Our results highlight the significance of sketching in the creative process for idea generation and design thinking, as well as for the digital process. Based on the results, we suggest that, compared to rating micro-tasks, selection

micro-tasks yield output of a more manifest and distinct quality. Our results also highlight the importance of taking into account psychological considerations, providing designers with a brief in advance, and encouraging competitive spirit among the participants of crowd-sourcing projects.

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# Dance with Shadows

## *Capturing tacit knowledge with smart device augmented reality (SDAR)*

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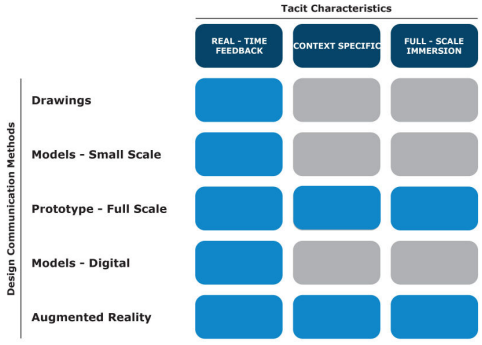
*Tacit knowledge has been notified with its involvement in the creative and innovative process of design. However, it has been an elusive subject due to its difficulty to be articulated, recorded, and communicated. Augmented Reality (AR) is introduced as an affordable, accessible, and collaborative way to revisit tacit knowledge in the design process. In this paper, a computational design approach with Smart Device Augmented Reality (SDAR) is proposed for a real-time fenestration design in a targeted room. In comparison to standard methods of showcasing daylighting metrics, the use of Smart Device Augmented Reality (SDAR) is an alternative method as it delivers a dynamic experience by combining both the real and digital environments, enabling the visualization of the design in its intended site context with real-time feedback. The implementation of the proposed approach is explained and the design process with SDAR is also demonstrated in this paper.*

**Keywords:** *tacit knowledge, augmented reality, simulation, real-time feedback*

## INTRODUCTION

Tacit knowledge is personal, practical, and context-specific to the extent that even the knowledge-holder may not be aware of its existence. Terms like "intuition", "know-how", "procedural knowledge", "implicit knowledge", "unarticulated knowledge", and "practical or experiential knowledge" have been used to describe tacit knowledge (Ambrosini and Bowmand, 2001; Polanyi 1962;1966). Because of its importance in combination with explicit knowledge (Nonaka and Takeuchi, 1995), various ways of applying and transferring tacit knowledge have been made. However, due to the difficulty of capturing or representing tacit knowledge in explicit form, communication with tacit knowledge still remains problematic (Dampney et al, 2002). Especially in architecture, its design communication comprises unique dispositions, possessing specialist knowledge, skills, and education. They are socially acquired through experience and practice, and continually reproduced over generations (Sandstrom and Park, 2019; Stevens, 1998; Bourdieu, 1977). In addition to natural language descriptions, drawings, physical & digital models, and various simulations have been the primary media of architectural design communication. In order to address the difficulties of design articulation within the role of conventional design communication media, Augmented Reality (AR) has been introduced to architecture.

Coined by Caudell and Mizell who worked for Boeing Company in 1990, the term Augmented Reality (AR) serves to create a reality that is supplemental to the physical environment (Caudell and Mizell, 1992). By adding an enhanced layer of computer-generated information to the real-world environment, AR allows a user to deal with 1) real-time feedback, 2) context-specific experience, and 3) full-scale immersion of its simulated reality. They become the instrumental features of the embodiment of tacit knowledge (Figure 1): 1) real-time feedback: users, clients, and professionals alike are encouraged to engage in interpersonal communication to enhance the quality of design decision making, 2) context-specific experience: users are able to experience design in the proper context of existing site conditions, 3) full-scale immersion: users are able to experience the design's proper scale allowing interaction with a given design space prior to project implementation (Sherman et al, 2019; Carmigniani and Furht, 2011; Yang, 2011).




With the advantages, AR has been employed in the design process for 1) developing a comparative analysis between physical and augmented modeling interactions (Webster et al, 2000), 2) providing a real-time interactive instruction for the assembly of a modular system (Kontovourkis et al, 2019; Kim et al, 2013), 3) assisting architectural design and communication with a user's immersive experience (Hsu, 2015; Danker and Jones; 2014). Compared to other media including drawings, physical & digital models, and Virtual Reality, AR provides better interpersonal experiences (Lawrence,1993).

AR systems have been developed with two different types of displaying devices: Head Mounted Displays (HMDs) and Smart Device Augmented Reality (SDAR). Through an optical see-through and gesture-controlled headset such as the Meta 2 display, DAQRI's Smart Helmet, and Microsoft's Hololens, HMDs provides the direct view of the real world in order to avoid distorting or reducing the user's view of the real environment. The enhanced information projected into the user's eyes is interactive to the user's head and body movements (Kontovourkis et al, 2019; Azuma, 1997). SDAR is achieved through the use of various devices including smart phones and tablet PCs so that the viewer of SDAR holds a device where the screen is in conscious awareness of the viewer. Also, the versatility of the smart device allows a user to explore outdoor environment and lighten up the learning curve of finger gestures to perform a given augmented reality. Furthermore, the collaboration of multiple users within SDAR provide bilateral design experience using built-in functions of the smart devices (Azuma, 2014; Hsu et al, 2013).

In this paper, Smart Device Augmented Reality (SDAR) is employed for investigating an alternative design method for implementing real-time feedback, context-specific experience, and full-scale immersion that embodies the essence of tacit knowledge into a design process. The proposed smart device augmented reality (SDAR) application consists of Rhinoceros 3D, Grasshopper3D and Fologram. It is applied for a fenestration design with daylighting metrics. The application allows a user to articulate the design's proposal not only by visualizing in a real-time environment but at the same time engaging themselves in the decision-making process. Through this iterative design communication within the proposed SDAR, the tacit knowledge involved in the fenestration design is shared among the stakeholders of the design. This investigation, however, does not intend to replace conventional design communication

Figure 1
Instrumental features of the embodiment of tacit knowledge

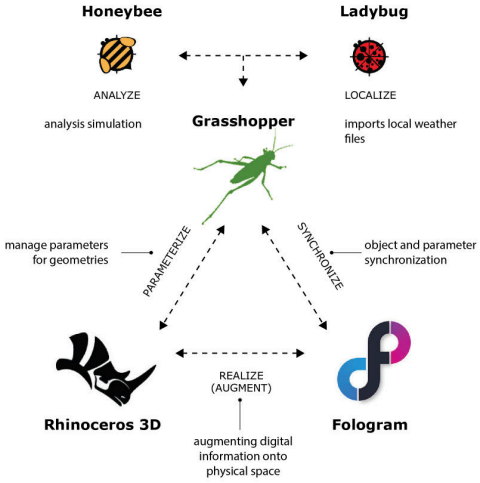
media, but instead to introduce the SDAR application as an additional layer where deemed appropriate.

## SDAR: A FENESTRATION DESIGN WITH DAYLIGHTING METRICS

### *Framework*

This SDAR application is developed for achieving 1) a real time feedback from the analysis with the visualization of daylighting metrics for a specified room, and its synthesis accordingly, 2) a context specific experience with the mobility of a smart device and its convenient usage, 3) a full-scale immersion with the interactive control of the application. Rhinoceros 3D and visual programming language Grasshopper 3D are supported by plug in applications: 1) Ladybug, 2) Honeybee and 3) Fologram (Figure 2). As a smart device, iPhone 8 with 2GB ram and 12MB pixel camera is employed.

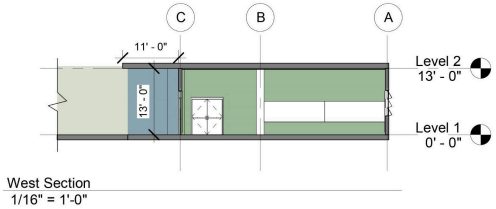
Figure 2
Framework




This proposed application consists of 1) initiation of SDAR, 2) analysis of daylighting metrics, 3) synthesis of the fenestration, and 4) simulation of the synthesis outcomes. SDAR is initiated Fologram within Rhinoceros 3D. Its location is adjusted with a marker.

A classroom in Honolulu, Hawaii, was built in the digital model for the project and its coordinates were used for gathering the annual data set of the daylighting metrics on the site. Its section view was shown in Figure 3.

Figure 3
Section view




### *Initiation of SDAR*

Fologram, a mixed reality application, was chosen because of its stable synchronized live stream with Rhinoceros3D and Grasshopper3D. Also, it works across multiple platforms - Hololens, iOS, and Android (Figure 4). The live connection of the device is established by scanning the QR code. A special marker is used for finding the correct location of the given geometry from Rhinoceros 3D as shown in Figure 5.

Figure 4
Fologram Interface of a Smart Device

Figure 5
SDAR initiation a) QR code b) Marker

### *Analysis: Daylighting Metrics*

This application allows a user to perform the analysis of daylighting metrics including 1) illumination (Figure 6), 2) radiance, 3) solar exposure (Figure 7). Honeybee and Ladybug, Grasshopper plug-ins, are integrated into this process where Ladybug allows us to utilize local weather data and Honeybee uses that weather data to run an analysis simulation of the desired space. Coupled with Fologram, the combination of these plug-ins allows the user to achieve visualization of daylighting metrics layered to a real environment (Figure 8). The user is put into the full-scale real room environment where the user can conduct a full interior walkthrough within the augmented space. By setting up the date and time of the analysis according to the targeted time period, the user also achieves the context-specific experience.

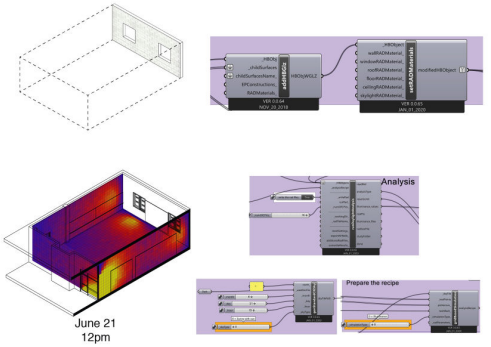



Figure 6
Daylighting: Illumination

In addition, daylighting metrics, the user is able to analyze radiation maps in full context. This could inform the design of the fenestration so that radiation accumulation would not impact important areas within the room as it is being absorbed.

Similarly, with sun exposure, the user can visualize the amount of sunlight hours that falls directly on a surface in full context. This information may be looked at in parallel to radiation. With the daylighting metrics analysis, the user is be able to see where in particular that generates illumination, radiation, and sun exposure. The analysis of the daylighting metrics becomes a valuable source for the design of the fenestration.

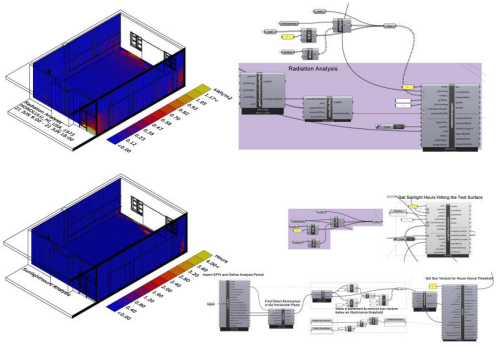



Figure 7
Daylighting: a) Radiation b) Solar Exposure

On the layers tab of Fologram's user interface, the synchronized objects are displayed. The user may toggle on and off to control the visibility of the synchronized object. Sliders, Buttons, and Value lists are the current three parameters that can be synchronized to Fologram's interface. The user drops down the menu initiating one of the daylighting metrics in the fenestration's original state.

Figure 8
Analysis: a) Interface b) Illumination outcome

Figure 9
Synthesis: Initial Setup

Figure 10
Synthesis: Addition, Deletion, and Translation

Figure 11
Synthesis: Changing the width and height of the opening

### *Synthesis*

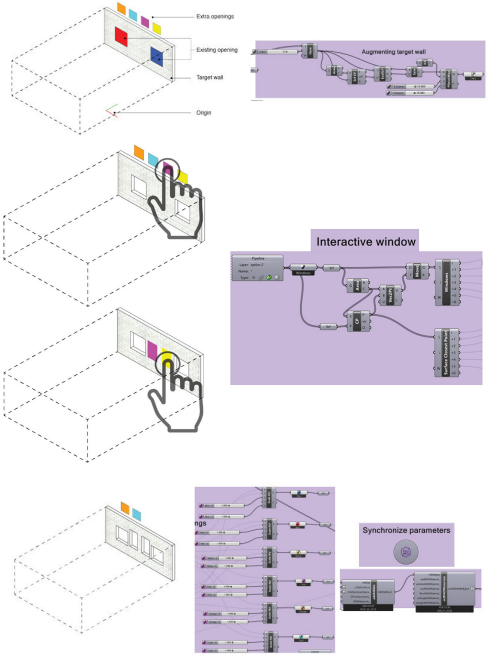
The analysis outcomes of the daylighting metrics become the resources for real-time feedback in order to perform the synthesis of the fenestration design. The user is in full control of the actions taken while they are being overseen by the mentor. This is achieved by allowing the user with professional guidance to (1) the addition and deletion of the openings, (2) the translation of their location, and (3) the modification of their sizes. After the synthesis, the user re-initiates the simulation to see how their new opening configuration would affect the daylighting analysis results in conjunction with the current real-time environment.

Each window opening is color-coded for the ease of object-parameter correlation (Figure 9). When viewing the opening the user may toggle on and off a specified color according to the location of the opening in the layers tab.

On the smart device, adding or subtracting windows is done through holding and dragging on the touchscreen canvas. The color-coded window indicators located above a target wall are used to add additional openings to the wall. Similarly, for the deletion, the user may simply swipe and place it anywhere off the target wall. In parallel, the translation of the window is the same by holding and dragging to any designated area of the target wall (Figure 10).

When the user is satisfied with the general window location, the user can then modify the size of the openings (Figure 11). These changes are made through parametric sliders in Grasshopper 3D as shown below. Each color-coded window opening is paired with a set of parameters that can control the width and height of the opening. The parametric sliders become the part of the user-interface on a smart device.

The synthesis process on the user-interface of the smart device consists of 1) selection, 2) addition & deletion, 3) translation, 4) modification as shown in Figure 12.



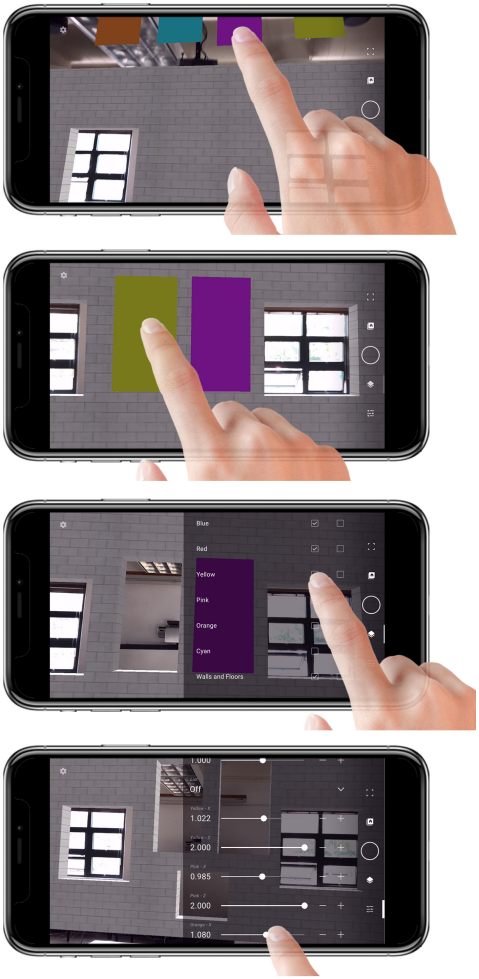



Figure 12
Synthesis: Process

### *Simulation*

After confirming the new composition of the window openings, the user may then re-initiate the analysis. The results are reflected by the user's changes. The floor directly below the newly created openings show greater illumination results. With these new results the user can visualize and conduct a walk through in full context of the augmented environment (Figure 13).

The iterative cycle of the user engagement procedures including initialization of SDAR, analysis, synthesis, and simulation creates a dynamic interaction between designer and the user. By going through this cycle, the user articulates the design through visualizing in a full-scale context with learning valuable knowledge as they learn through their own actions with guidance from the designer.

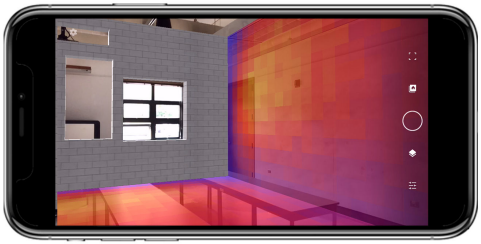


Figure 13
Simulation: Outcomes

## DISCUSSION

In this paper, Smart Device Augmented Reality (SDAR) was employed for investigating an alternative design method for implementing real-time feedback, context-specific experience, and full-scale immersion that embodies the essence of tacit knowledge into the design process. Real-time feedback was witnessed as users were directly engaged in the modifications of the openings, while being mentored by the designer, initiating constant communication after each decision made as they reflect on the analysis results. Users modified designs in the physical context of the room, looking at how their changes affect the interior daylighting on surfaces (floor, walls, desks, etc.). To provide full-scale immersion, the user was able to reference other existing elements within the room when size and location height considerations were being made while designing. Within the given SDAR, the user was directly engaged with the design, while being mentored by the designer. Design engagement procedures include 1) adding and subtracting windows, 2) translating the windows,

and 3) modifying the sizes of the openings via parameters. Toggling through the layers tab to show the opening in the wall, the user was able to initiate the simulation for conducting a full interior walk-through. This walk-through provided the user with a better understanding of future design iterations as they compare the analysis metrics against reality.

Since SDAR technology itself is in the early stage, there are shortcomings to be improved. First is a clipping plane issue. Within the proposed SDAR project, the augmented objects always appeared in front of everything physical even though they are behind the physical, hindering a user's full-scale immersion. Second is an unstable marker placement. It requires constantly scanning the marker in order to anchor the augmented object to an intended location in a given context. Third is a heavy processing load for performing the daylighting analysis within a smart device, and the last is a crowded user-interface due to the limited screen size of a smart device (Figure 14).

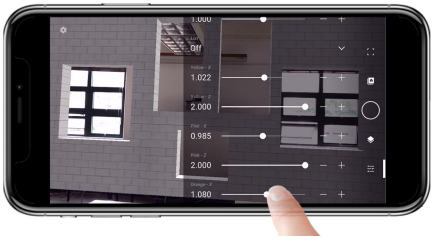



Figure 14
A crowded user-interface

Currently, two further directions are being pursued. One is a different type of AR system. In parallel with a smart device, the usage of Head Mounted Displays (HMDs) is developed for enhanced full-scale immersion. The other is to expand the application of the proposed SDAR to various performance-oriented designs not limited to daylighting metrics.

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# INTERCOM

## *A platform for collaborative design processes*

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*The INTERCOM project propounds a cloud-based collaboration platform for digital planning processes in architecture. The concept is based on an openBIM approach and ensures open access for all partners involved. At its core it provides IFC-based and model-related online tools for planning, communication and collaboration. The interaction with the model and the exchange with other project partners takes place in real-time via a model-related chat and BCF exports. In addition, the integration of e-learning modules (e.g. video tutorials, wikis, project documents) encourages problem solving through further education. Especially the integration of communication and collaboration tools is supposed to enhance the decision making throughout the design process and become a key factor for a successful and coordinated BIM process. Primarily INTERCOM has been developed as a prototype for teaching BIM in interdisciplinary teams. Subsequently, the application can also be adopted for professional practice. The paper evaluates previous experiences from BIM cloud teaching and discusses the conception and development of the proposed collaborative platform.*

**Keywords:** *architecture curriculum, didactics, building information modeling (BIM), collaborative design process, common data environment (CDE)*

## INTRODUCTION

Due to the structural change caused by digitalisation in the building industry and the evident demand for increasing productivity with simultaneous lower consumption of resources and energy as well as lower emissions, today significantly increased demands are placed on the planning and coordination services of all actors involved. Future development processes, from the planning and construction phase to the operation of the building, are therefore increasingly based on the principles of Building Information Modeling (BIM). In addition to the advantages of consistent 3D planning, this method places new demands on all project partners (Borrmann, 2018).

BIM thus primarily causes a change in the way we work. Even though the computer is an effective interface for the cooperation of different parties in the AEC industry, the success of a project depends decisively on the socio-cultural imprints and disciplinary boundary conditions of the people involved. In addition to the technological challenges of digitalisation, the different working methods, require-

ments and objectives often represent a threshold to successful cooperation and implementation of construction tasks. As academic institution, we are called upon to point out new paths that are geared to the future requirements of our professions and at the same time integrate individual professional profiles (Luckner, 2018). This is where the *INTERCOM* concept comes in, providing an infrastructure for students and lecturers that is independent of time and place and enables a consistently integrative and digital planning process, taking into account learning formats for collaboration and interdisciplinary communication.

## BIM CLOUD TEACHING

Although integral planning methods are discussed widely in the AEC industry, a holistic approach of BIM is hardly present in the architectural curriculum and computational design in architecture is still quite often addressed in the sense of traditional CAD teaching programs (Stellingwerff, 2018). Existing software solutions are usually not designed to be used within a holistic university context, but rather aim at providing individual solutions with separate data management. Furthermore, working in proprietary file formats of individual software packages offers little flexibility and exchange possibilities. Therefore, the potential of cross-disciplinary cooperation cannot be comprehensively reflected in teaching at present: There is a lack of appropriate learning environments as well as didactic concepts for teaching and moderating digitally networked processes (Garner, 2011). Against this background, the two academic projects *MilanSky* and *INTERACT* tried to establish a common data environment (CDE) based on a BIM cloud server to experiment with an integral and holistic planning process.

### *MilanSky - collaborative high-rise building*

The *MilanSky* project emerged from an interdisciplinary course at Milan Polytechnic University, which focused on the collaborative aspects of BIM. Based on the task to design a new skyscraper at the recently re-developed Porta Nuova district in Milan, the aim of the project was to establish an integral planning approach in a cooperative working atmosphere. The process was set-up and monitored within a cloud-based environment (Autodesk BIM360 [1]), allowing ubiquitous access throughout the entire design and planning phase. The decision to organise the different building parts within a central BIM data structure was taken, since consistent planning and coordination of various technical, functional and programmatic aspects was particularly important.

The course was conceived as a bottom-up process, starting with a *concept phase* that generated various ideas and topics for the development of the skyscraper design. From there, so called *global topics* were extracted that served as a starting point for an in-depth planning phase, focusing on the following ten aspects: design concept, context, program, energy, structure, technology, façade, tradition & innovation, sustainability and project management. For the implementation and coordination of all aspects in play a centralized BIM model was set-up that served as an operative platform for the further project development. Besides the responsibility for a *global topic* the student teams were also in charge of one specific high-rise floor. The design of these *local floors* had to take into account the *global topics*, the overall appearance of the building and the connections to the adjacent storeys (Figure 1).

The BIM cloud environment served as an operative platform for the planning process and the monitoring of the design development. However, beyond the object-oriented building data modelling, the communication process and collaborative workflow was not mutually supported by the platform. The decentralised exchange of information as well as consultation and decision making was time-consuming and in strong contrast to the integral design approach.

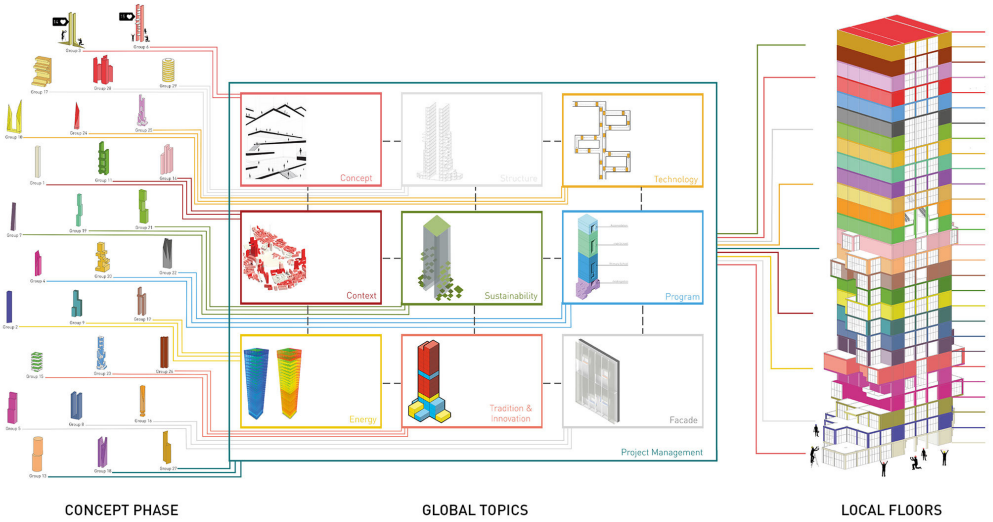


Figure 1
Visualisation of the MilanSky design process in three steps: individual concept phase (left), common development of global topics (middle) and collaborative design of the local floors (right).

### *INTERACT - Laboratory for Architecture, Crafts and Technology*

The MA course *INTERACT* at Cologne University of Applied Sciences also aimed at an integral design process, incorporating all students and lecturers into a CDE. A group of 25 students from different specializations within the architectural master's program worked together on the design of four new laboratories to be built on the university campus. The temporary construction includes a workshop, a material library, an exhibition pavilion and student studios as well as a wooden platform that serves as a common base for the buildings.

The design process of each building and the platform was distributed to groups of five students, which had to coordinate their concepts with the other groups. The platform group in particular played a special coordinating role, as the positioning and orientation of the pavilions as well as the routing had to be coordinated and integrated into the overall planning.

Here too, the Autodesk BIM360 platform [1] provided a good starting point for collaborative design development as well as visualization of collisions and conflicting goals (Figure 2). However, the communication process again ran largely in parallel to the planning process. Since the group was smaller and also more connected outside of the contact hours than in the *MilanSky* project, the coordination worked somewhat better. Nevertheless, a lot of additional time was spent on decentralized coordination, which in turn led to planning mistakes, time loss and misunderstandings.

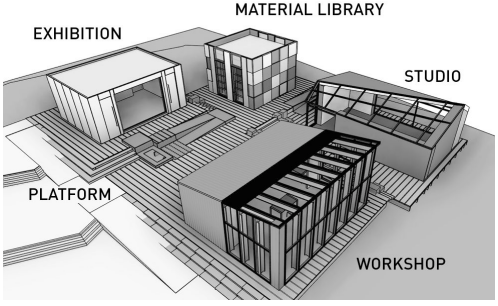


Figure 2
BIM model of the INTERACT Lab, consisting of a wooden platform, a workshop building, an exhibition pavilion, a material library and student studios on the campus of Cologne University of Applied Sciences.

## INTERCOM PROTOTYPE

These initial experiences with BIM cloud teaching show quite clearly that there is a need for model-related communication and collaboration in order to integrate decision-making and coordination processes in addition to purely creating a data building model (Figure 3). Especially in the academic context, these additional tools would offer good opportunities to support the teaching and learning process, in which eLearning modules could be directly linked to the BIM planning process.

Figure 3
Conceptual design of the INTERCOM platform for collaborative design processes.

### *Objectives*

Against this background, the aim of the *INTERCOM* project is to establish a cloud-based openBIM teaching platform, integrating various communication and collaboration tools as well as further learning resources. It should enable viewing, processing and assessment of BIM design data in a location-independent learning environment, which is equally accessible for students and lecturers. In addition to the technical advantages of up-to-date project data, the platform is intended to enable a deeper, more active and flexible discussion between participants around the specific project. To reach this goal, the INTERCOM project pursues three main objectives:

**Building a cloud-based learning platform.** Although the cloud-based approach is used in current software solutions, it is not geared towards open teaching formats with integrated options for communication for larger groups of students. The aim is therefore to create a process-oriented learning environment that makes constructive use of the heterogeneity of the students and encourages them to act and learn in a team environment. The content and project-related 3D data generated in teaching should ideally not be placed on individual computers, but be made available to everyone, centrally and web-based, from anywhere.

**Interdisciplinary cooperation.** BIM thrives through the cooperation between disciplines. Therefore, an important aim of the project is to create a common education platform that gives all respective institutes and disciplines access to this planning method. This also includes the joint development, mediation and moderation of cooperative design and planning tasks. Moreover, open standards should enable the data and information exchange.

**Development of an integrative BIM curriculum.** The introduction of an openBIM teaching platform could provide access for less digitally oriented disciplines as it's not based on specific software, but offering open access to data and information exchange for the entire project team. Against this background, the possible cooperation of different disciplines in teaching on the basis of 3D building data needs to be examined. The research therefore aims to gather experience, evaluate processes and use them for the further integration of BIM in the curriculum.

### *Conceptual Design*

The *INTERCOM* platform is intended to combine various communication and collaboration methods with the building data model in a practical way and thus meet the high coordination requirements in the design and planning phase. In addition to the previously referred objectives, the following operational and didactic advantages of the intended *INTERCOM* platform have been targeted:

- Interaction with the model and communication with the project participants in real time.

- Moderating support by lecturers and evaluation of the development by all participants within an active data set.
- Lecturers and students act at eye level in a CDE.
- The learning platform enables individual and demand-oriented learning while at the same time offering consultation via direct feedback management.
- Integration of various e-learning tools (chats, video tutorials, wiki), ideally generated and updated by students as part of their learning outcome.
- Reliable project and user-related access and permissions management.

### *Technical Architecture*

Since the software development capacity has been limited within the project set-up, the focus was to reuse (open-source) software solutions as much as possible, linking together previously existing technologies and providing a cohesive interface to the user (Figure 4).

- The foundation of any collaborative work on *INTERCOM* is the project's 3D openBIM data, which currently is based on IFC import. The geometry and materials are used to shade and display the model and allow the user to navigate the virtual space. The GUID and class of each building component is used to link to additional resources.

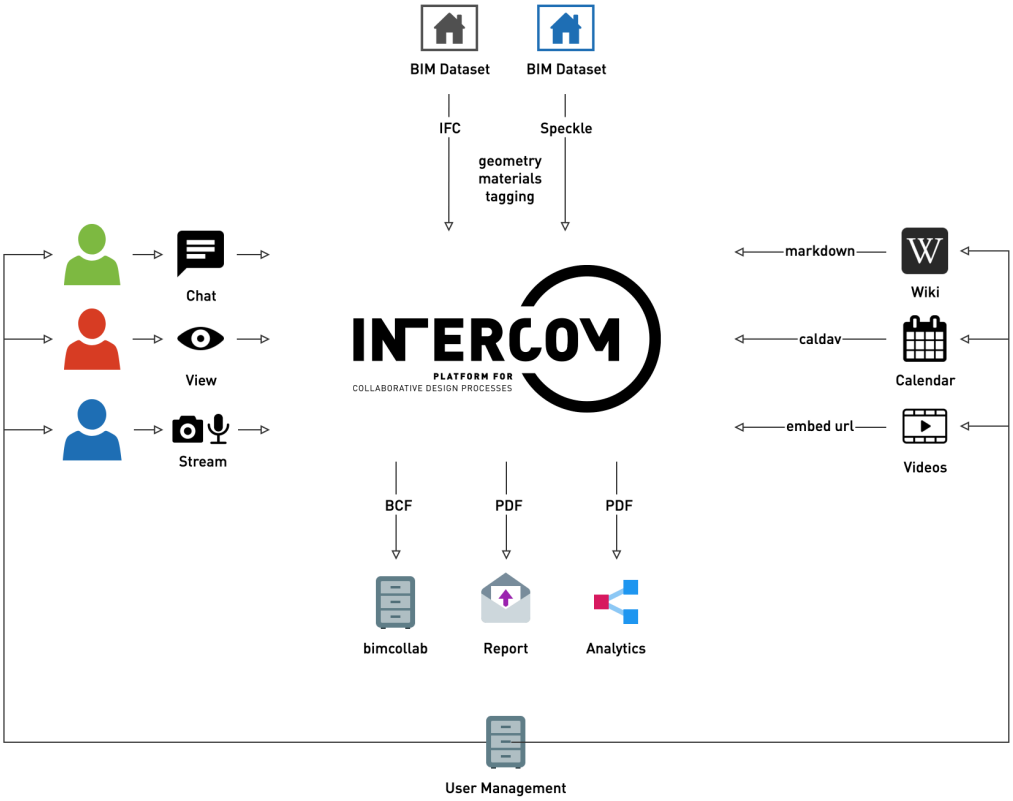


Figure 4
Technical architecture of the INTERCOM platform

- The main user interaction is similar to conferencing systems, allowing text-based, audio, video and screen-sharing communication. Additionally, since each user at each moment has an individual perspective on the current 3D model, it is possible to invite other users to *see what I'm seeing*.
- Additional information is stored in standardized wiki, calendar and video systems and is linked dynamically into the *INTERCOM* platform using tags, which can be assigned manually by project managers or auto generated using the components classes, i.e. *IfcRoof*.
- Through the BIM Collaboration Format (BCF), it is possible to archive decisions and discussions, using the GUIDs of individual components, and import them back into specific BIM software packages for further development of the project.
- A central authentication system reduces complexity for the users and makes it easy to participate in making their learning outcome available persistently to others through the linked knowledge bases.

The unreal engine [2] was chosen as the technical framework to develop the prototype due to pre-existing experience and it's extended capabilities in rendering and interacting with 3D data (Figure 5). Additionally, a custom module was implemented to sync user data and communication between multiple running instances using a socket.io [3] server.

With the prototype, after logging in and importing a dataset for the current session, this is the interface a user is presented with. [figure 5] On the left, information about the dataset and the currently selected component is displayed. Here the user can create a BCF issue for it or access related information and knowledge from linked sources. On the right, the user is able to access the communication channels as well as visibility and perspective settings .

Other users currently participating in the session are listed and displayed as *camera avatars*, providing a sense of interactivity and previewing the possibility to switch perspective.

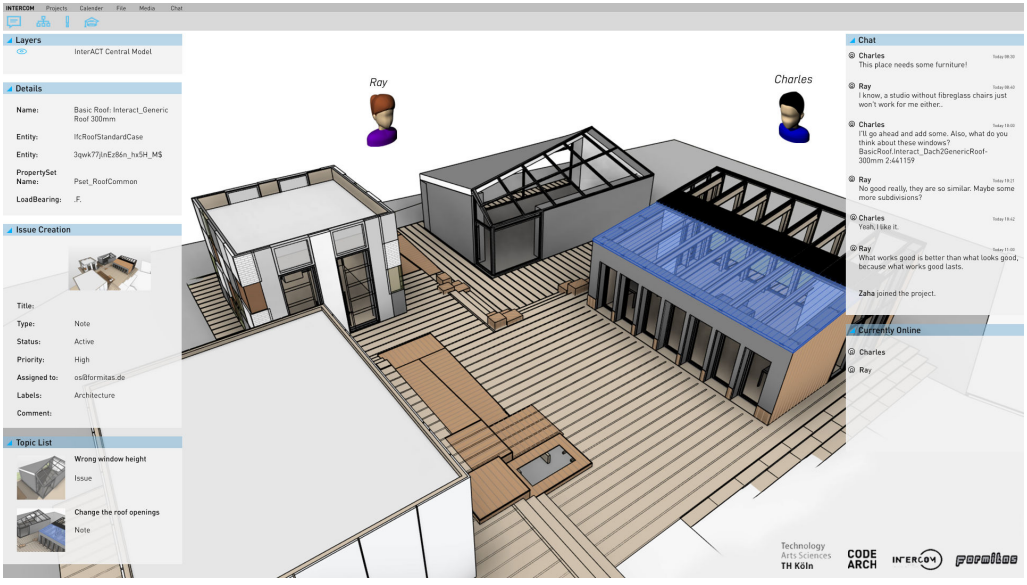


Figure 5
INTERCOM prototype based on unreal engine

## DISCUSSION

The introduction of *INTERCOM* into courses will be performed in stages, with increasing demands on the learning platform (degree of networking, number of project participants and complexity of the planning task), so that findings and experience can be successively incorporated as the project progresses. An accompanying process monitoring is to identify potential problems in the technical implementation at an early stage. The inclusion of the faculty and university IT should also ensure a functional connection to existing IT infrastructure. Increased attention was given to data protection and data security, since the fundamental idea of an open infrastructure, which is accessible to everyone at all times, requires a working environment that is both protected and secure.

Beyond the technical and functional evaluation, the main focus is on the assessment of the intended learning outcome for students and the intended collaborative planning processes. For this purpose, different surveys are planned in the course of the project. After each of the three planned introductory stages, a comprehensive evaluation will be conducted with the students using questionnaires, interview formats and Teaching Analysis Polls (TAPs). Target group specific surveys and peer group feedback will also provide information about the success of the project from the point of view of the various project participants.

An essential prerequisite for the success of *INTERCOM* is the willingness of all participants to make comprehensive process changes. Working on a common data set in the cloud requires not only technical training, but also indispensably the mediation of a different social interaction - from *I* to *We*. The proposed platform offers an appropriate learning space for this and promotes exchange by defining a common scope of action for all participants from the very beginning. The success of the whole depends on the contribution of each individual. This applies to students as well as to lecturers. In the best case, this creates a conscious sense of community and responsibility among all those involved, which makes a decisive contribution to the success of the project and the learning outcome.

## OUTLOOK

### *Curricular Development*

The integration of the cloud-based learning platform into the curriculum of the architecture course is planned in three stages:

**BA compulsory module.** *INTERCOM* is initially to be used as a component of basic teaching program in the Bachelor curriculum. Within the framework of the compulsory module *Planning Management* the platform will form the main focus in the third semester, after the second semester will introduce the basics of digital design and representation.

**Inter-institute BA elective module.** In cooperation with other institutes of the faculty of architecture, elective modules are to be offered which, in addition to design and construction aspects, also integrate sustainability criteria for climate-friendly and energy-optimised construction as well as for process and cost management.

**Cross-faculty MA elective module.** The extension of the concept to collaborations outside the faculty or university is intended as a third development step. The Masters elective module *cross-disciplinary design* aims at the realistic depiction of an integral planning process with different project participants and requirements relevant to practice.

### *Web-based Platform*

During the development of the current unreal engine-based prototype it became apparent, that while unreal engine is great for the early prototyping phase, since many of the visual and geometric operations are comparatively easy to implement. This has allowed iterating on the design and technical architecture of the prototype very quickly. However, it has also come at the cost of scalability and the integration of communication technology has become increasingly difficult.

Since the communication and interlinking modules of the *INTERCOM* platform are essentially core web technologies, a move to an entirely web-based code base is currently being evaluated. Using existing open-source libraries like IfcOpenShell [4] and babylon.js [5] a promising proof of concept has already been started, which will hopefully be ready to be shared with the community in the near future. Moreover, projects like bimserver [6] and newer actors like bimdata.io [7] and bimspot.io [8] have been acknowledged for solving some of the problems at hand.

### *Alternative Data Pipelines*

While the *INTERCOM* platform is currently based on the openBIM standard, the future development could integrate other open data platforms like speckle.systems [4]. Due to the modular design of *INTERCOM* it is easy to see these integrated as an alternative data pipeline at some point. The significant advantage of such a streaming data pipeline would be, that it eliminates the need for importing IFC datasets and instead provides better real-time interaction between existing software packages and the *INTERCOM* platform. Alternatively, a connection to existing BIM cloud products or simply a shared file server could be possible ways to make the underlying building data more up-to-date and available in real-time.

## ACKNOWLEDGMENTS

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[3] https://socket.io/

[4] http://ifcopenshell.org/

[5] https://babylonjs.com/

[6] https://github.com/opensourceBIM/BIMserver/

[7] https://bimdata.io/

[8] https://bimspot.io/

[9] https://speckle.systems/

# From Analog to Digital: Double Curved Lightweight Structures in Architectural Design Education

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*The paper describes an architectural design studio for 5th year students at the Department of Architecture of the Aristotle University in Thessaloniki, Greece. The educational objective of the studio is the design of double curved lightweight structures, employing a creative methodology which instrumentalizes the study of nature as a source of inspiration. The objective of the course is to familiarize the students with curves and form-finding (analogue and digital) with the aim to design forms that display structural stability. The paper will highlight the educational gains from a hybrid design methodology which employs both analog (physical) form-finding tools and digital modeling for the design of double curvature surfaces.*

**Keywords:** *Lightweight structures, Form-finding, Dynamic models, Tensile structures, Architecture education*

## INTRODUCTION

The well-established design methodology of form-finding is historically based on the construction of "dynamic" models (Otto & Rasch, 1996). The "dynamic" model incorporates the forces acting on the model, therefore simulating its mechanical and structural behavior, while driving the designer towards structurally efficient constructions. The use of "elastic" material for the design of membranes contributes to the form-finding of double curvature structural surfaces which are anticlastic (tensile), or synclastic (inflatable). Frei Otto referred to these as natural constructions, not merely for their morphological resemblance to natural forms but mainly because "these are constructions which reveal the processes of their creation with particular clarity. The form-finding processes are those which, given a set of conditions and following the prevailing laws of nature give rise to visible forms and constructions under experimental conditions. As they take place without human intervention they are also termed autonomous formation processes" (Barthel, 2005).

Within the studio set-up, the small-scale "dynamic" model is a useful methodological tool for future architects to experiment with form-finding, to understand forces of tension and to create optimized solutions which integrate design and structural decisions (Otto, 1988, 1990). This methodology pro-

vides an experiential learning environment offering the opportunity to work hands-on and create low tech models with high tech logic.

Parallel to the construction of small-scale "dynamic" models, the students experiment with dynamic relaxation in Rhino with Grasshopper parametric design plugin and Kangaroo Physics engine (Piker, 2013). Digital simulation allows designers to investigate forms by updating forces, supports and physical properties. The course focuses on both the analog/physical and the digital form-finding, not as two competing design strategies, but as two design methods which act synergetically giving feedback to each other, a hybrid design process in a digital-material environment.

## A TEACHING METHODOLOGY WITH PHYSICAL MODELS IN THE DIGITAL AGE

The transition from analog to digital architecture is in progress for some time already. Today we are going through a period, during which artificial intelligence, augmented reality and material intelligence define the new environment in which the educational discourse of architectural theory and practice is being developed. This new reality equips the contemporary architect with new tools both in the design process (novel software) as well as the construction process (digital fabrication).

At the same time, however, it raises a number of concerns and questions about the necessity of empirical practice in architectural composition: In the age of 3d printers and robots is it still necessary for students to construct physical models? How is the knowledge gain enhanced with the use of hanging chain networks, stretched fabrics, soap films?

According to Aristotle (Barnes, 1982), man creates Art and Science using his mind-based experiences. By translating this to the field of architecture, the students' experience of developing physical models, combined with intelligence, can lead to a deeper understanding of their compositional choices - an understanding of the main rule that governs and organizes the elements of their construction. Within this framework the design studio will initially follow a hands-on approach. Experiential learing has a series of undoubtable benefits, Kolb advocates that active learning pedagogies are of a very high educational value (Kolb, 1984), he elaborates saying that hands-on processes, followed by critical reflection and experimentation lie in the core of the learning process. In an era, when architecture is dominated by digital design processes, it becomes increasingly important to engage with analogue design media, and understand the correlation between analogue and digital tools. As the students were setting up the models literally "with their hands", they subconsciously obtained the tacit knowledge about material behavior and the way forces translate into geometry.

## FAMILIARITY WITH DOUBLE CURVATURE SURFACE GEOMETRY

Among the initial design exercises to familiarize students with geometry, is the discretization of doubly curved surfaces. The aim is to constructed a series of 3D primitives with flat sheet material, to assemble curved cylinders, curved cones, saddles and hyperbolic paraboloids or forms obtained through combinations of the above.

A rigid and flat material, such as paper, can only bend in one direction and if one tries to bend it in two directions it will crumple or tear apart. This is due to the fact that non elastic material can only create a surface of single curvature such as a cone or a cylinder but not an ellipsoid or spherical solid, that is to say, surfaces of double curvature.

For the construction of double curvature surfaces, the rigid material should be cut in discretized shapes (patterns) that when joined together will approximate a doubly curved surface (M. Kilian et al., 2008; Tachi & Epps, 2011). In this way basic geometric forms are constructed, and through this process the students are able to experience a hands-on process of design rationalization, understand how doubly curved forms may be discretized to planar or single curved parts and how these can be synthesized to generate a taxonomy of several doubly curved forms

that can be constructed out of cardboard in the design studio (figure 1). For example, through experimentation with the doubly curved cardboard models it appears that the hyperbolic paraboloid is derived from the curved semi cylinder (saddle) which in turn is derived from the curved cylinder (Figure 2).

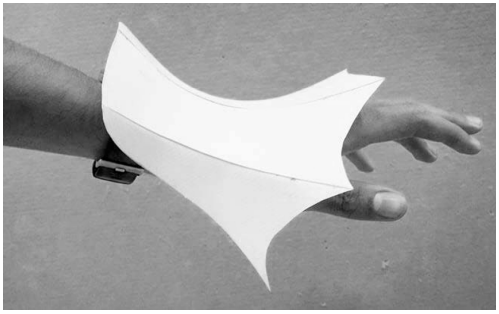


Figure 1
Cardboard model of a doubly curved saddle shape constructed from single curvature elements. Students: Moga M., Seferidis Z. Students: Moga M., Seferidis Z.

Figure 2
The curved cylinder and its subdivisions. From left: curved cylinder (silo), curved truncated cone, curved semicylinder (saddle) and hyperbolic paraboloid. Students: Drosouni A., Konstantinidis N., Ibanez F.

In this first introductory exercise, students become familiar with the geometry of basic double curved surfaces, mainly with regards to construction logics, rationalization and cutting pattern generation. At this initial stage, experimentation with doubly curved surfaces employs rigid material, therefore students are not yet aware of the forces exerted on these surfaces when flexible material is used in physical form-finding and the repercussion of the forces on their shape. This important consideration is to be discovered during the subsequent exercises in which students will experiment with "dynamic" models.

## "DYNAMIC" MODEL AND FORM-FINDING

The "dynamic" model is more than a three-dimensional object, as opposed to the aforementioned rigid models made of cardboard. The "dynamic" model responds to the forces acting on the model, the geometry is the result of the boundary conditions, the forces, anchorpoints and elasticity of the material.

Students experimenting with elastic fabrics and inflatables not only understand from the first moment the forces exerted on the structure, but also realize that these forces produce the form of the construction. Thus, students are encouraged to engage in an experimental design process that combines form-finding with the actual understanding of structural performance in real time. This experiential learning approach makes it immediately clear to students that for lightweight architecture, construction is not an independent stage, which follows the end of the design process, but is instead, from the outset, an integral part of architectural design in constant feedback with architectural composition. Thus, in the design studio the process of architectural design is linked to issues of construction, stability and materiality (Figure 3).

## STUDENT TASKS

The students experiment with dynamic physical models of lightweight structures, utilizing a variety of materials, as seen in Table 1

Within the category of tensile membranes the models manufactured are classified according to their supporting structure (poles, arches, space-frame) and their position in relation to the membrane (outside or inside) (figure 4) (figure 5).

Table 1
Models, materials, elements and mechanisms

| DYNAMIC PHYSICAL MODELS | MATERIALS | ELEMENTS & MECHANISMS |
|---|---|---|
| **Membrane Structures** (Retractable – Foldable - Self-supporting) | Metal Rods or Timber Elements, Elastic Fabric, Lycra, Wire, Thread | Hooks, Pulleys, Levers, Pin Joints, Scissors, Anchors |
| **Inflatable Structures** (Grid – Air Tubes & Cushions – Variable pressure) | Plastic membranes, Balloons, Biodegradable materials | Hooks, Anchors, Weights |

Figure 3
"Dynamic" model and form finding. Students: Amanatidou B., Radou D., Siapkari K., Fassa Th.

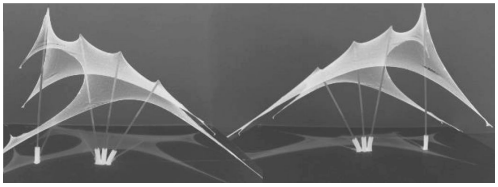


Figure 4
Tensile structure with poles. Student: Charalambidou M.

The models of self-supporting membrane structures are classified into two categories. In the first category the membrane is supported by a spaceframe or other primary loadbearing structure, in this case the membrane simply functions as a secondary element, it does not participate in the overal structural performance of the construction. On the contrary, in the second category the membrane plays a role in the structural performance, acting as a tension element that stabilizes the rest of the structural elements.

The models of the folding-retractable membranes are classified, according to the way they are deployed or collapsed, into the following categories: folding, rotating, extending-shrinking, nesting, sliding, etc. The models incorporate movement, which is achieved with the use of different mechanisms such as: knot - joint (hinge), telescopic mechanism, scissors mechanism, umbrella mechanism among others.

In the case of a collapsible membrane, therefore, the concept of adaptability comes into play. The design must facilitate quick changes from one condition to another, enhance the ability of the model to modify its morphological and functional characteristics, in order to adapt it to a number of variable factors such as the changing weather conditions.

Finally, students experiment with inflatable models which are classified into four distinctive categories:

- Inflatable models that take their form from a grid structure or spaceframe that surrounds them
- Inflatable models in the form of air tubes or airbags (combining positive and negative pressure)
- 3D printing of a non-elastic structure on an elastic inflatable membrane (Figure 6)
- Inflatable structures with internal pressure fluctuation. That is, structures that can change shape and function by controlling the internal pressure of the tubes from which they are composed (Figure 7)

## INSTRUCTIONS FOR MAKING "DYNAMIC" MODELS

The instructions given to students for the construction of the aforementioned "dynamic" models may be summarize in the following guildlines. The students were promted to:

- avoid flat sections of membranes, for both aesthetic and functional reasons, as double curvature surfaces contribute to the resistance against windload
- use pin joints instead fixed ones. An example of the above is the use of pillars that are anchored by cables to the ground. If the posts are fixed (embedded) in the ground, then the lateral forces bent them, while if they are not fixed, the forces penetrate vertically along the pillars, resulting in better buckling

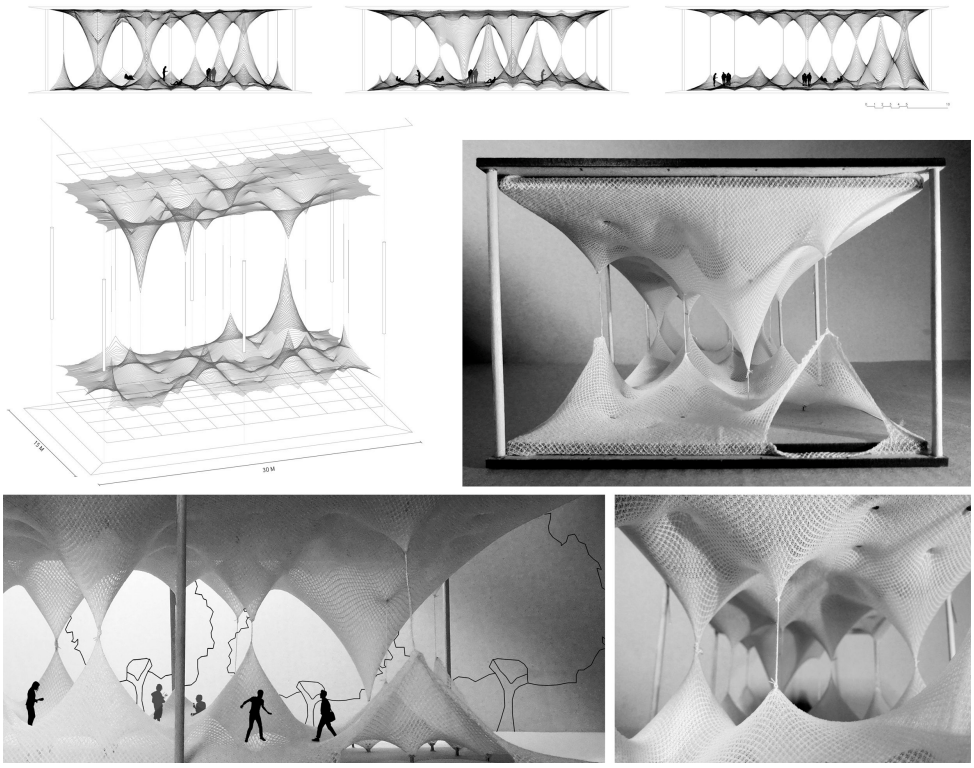


Figure 5
Multiple peak tensile structure suspended from floor and ceiling. The inverted peaks mutually support the tension of each side. The doubly curved parabolic surfaces form a "spiky" installation for walk and play. Students: Yagou A., Kasviki V.

- make the connection between the elements of the structure visible and clear
- ensure easy and fast installation and uninstallation of the structure
- emphasize the sense of lightness that governs lightweight constructions

Finally, in addition to the above technical and morphological criteria, students establish their own design decisions which may relate to different criteria and design parameters. To this end, each group of students creates their own scenario while taking into account not only technical and technological factors but also environmental, social and economic factors involved in the planning process.

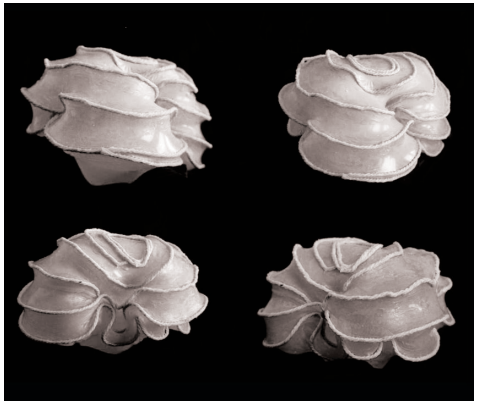


Figure 6
First step: 3D printing of a non-elastic structure on an elastic inflatable membrane. Second step: deflate the membrane to create hollow surfaces. Students: Mokka A., Mousafiri E..

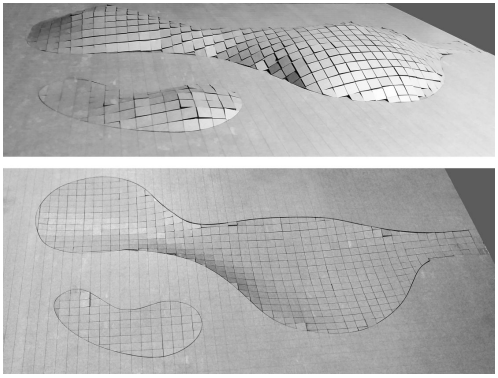


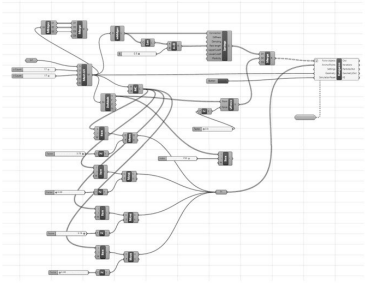
Figure 7
Dynamic inflatable structure at high pressure (above) and low pressure (below). Students: Goumenaki P., Beltou P.

## WAYS TO SOLVE A DESIGN PROBLEM

Observing the key cognitive manipulations with which students attempt to solve a design problem, it is found that the majority of students follow a mixed approach. There are several iterations of "trial and error", inspiration and rationalism, with a clear preference for exploratory approaches for the early stages of design. The hands-on approach proves to be of high educational value. Although unaware of the material properties and behaviour, students develop a variety of "accidental" reactions, by reflecting in action (Schon, 1984) in an exploratory environment where design solutions emerge through experimentation, knowledge, intuition and refinement. The students obtain tacit knowledge and understand the dynamic physical model as a vehicle for understanding the design characteristics of lightweight structures, the role of forces acting upon the model, and the emergence of form, the potential shapes that may respond to a design problem. Through such design experiments, "we can know more than we can tell" (Polanyi, 1966) and thus the students are able to design structurally efficient structures without the need for extensive and complex calculations. The great majority of students affirmed that hands-on-experimentation improved their understanding of structural behavior of the structures as well as computational thinking and that they were able to contextualize the empirical learning.

## FROM "DYNAMIC" MODEL TO DIGITAL

The "dynamic" model plays a crucial role not only in finding the form but also in understanding the interplay of underlying forces. The "dynamic" physical model is itself an example of computational design, we may refer to such models as analog computation, as they compute physical forces to reach a state of equilibrium. Having understood that, it was now easier and more intuitive for the students to engage in computational and algorithmic experimentations where physical forces are simulated and represented by a spring-particle model (Kilian & Ochsendorf, 2005). Therefore, students have only to transpose the internal logic of the dynamic model, a logic that can lead to a multitude of final forms by changing some parameters in the parametric definition. A membrane is described by a network of springs in Kangaroo (Figure 8), parameters such as stiffness, rest length, anchorpoints, etc are defined in the parametric model. The physics simulation will take place and an optimized and stable form will emerge as a result of the forces in play. This hybrid analogue and digital practice helps the students to understand the essence of computational design, the logic through which the form emerges, or rather a multitude of forms that are linked by a set of rules. There are many benefits of structural form-finding using particle-spring systems. A design exploration in this environment embeds criteria of structural optimization already from the early stages of the design process, while it assists architects to increase their intuitive understanding of the structural behaviour of geometrically complex forms. While traditional architecture and engineering aims at the structural optimization of an existing form, a dynamic form-finding system can lead to a "real time" discovery of structural form encouraging the morphogenesis of optimized structures rather than a post-design optimization. This justifies the methodological choice of the course to start with low tech models in an era of digital dominance.



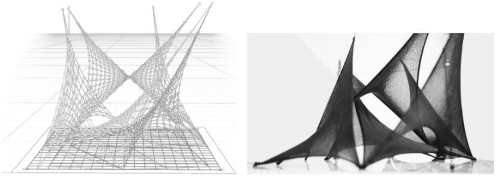


Figure 8
Analogue and digital models of membranes by students: Mitropoulou N., Podara A.

Figure 9
Construction of double curvature surface with non-elastic components. The cutting pattern is derived from digital processing of the dynamic model. Students: Dimitriadis A., Zygoulis N., Sakkas K.

## DESIGN AND CONSTRUCTION OF DOUBLY CURVED SURFACES WITH DIGITAL MEDIA

One of the most challenging issues for the design and construction of double curvature surfaces is the design of the membrane pattern (Figure 9). In the early days, designers used to apply glue to the fabric of the model in order to neutralize the elasticity so it could be cut into small pieces to form the cutting patterns on scale. From small (model) to large (real scale), they scratched the patterns with the use of a pantograph. This was the process before the emergence of computers (Tsinikas et al., 2019).

The advantage of digital design is therefore not only that it reduces the time it would take to develop and optimize the model compared to traditional design tools, but also because with the use of software a designer can generate construction drawings and detailing.

## CONCLUSION

The teaching methodology and the results of the design studio highlight the importance of a hybrid analog and digital design process, the reciprocal relationship between hands-on learning through physical models and the digital / algorithmic design processes. The main knowledge gain was the ability to understand the emergence of structural form as a result of forces and design decisions, through analogue or digital computation. As Wassim Jabi explains "Associative and parametric geometry, in essence, describe the logic and intent of design proposals, rather than the form of the proposal itself" (Jabi et al., 2013).

This exploratory teaching approach of the design studio confirms that the hands-on experience not only helps in finding the form and understanding of the logic behind the "dynamic" and digital model, but it also instigates students for further design research as they "play" with building materials, fostering teamwork and collaboration. Students acquired an intuitive understanding of what works and what not, and they were able to further conceptualize and understand the reasons of certain behaviour, they were able to develop what Albers referred to as "feeling for materials" (Albers, 2013).

From an educator's point of view, the idea of actively engaging in a hands-on exploratory process, both with analogue and digital media is extremely valuable for students for a variety of reasons relating to perception, cognitive psychology and learning theories. During the last decades there is a growing acceptance of learning-by-making, it is broadly recognized that knowledge is a consequence of experience and that the role of technology is significant in the construction of knowledge (Stager, 2014).

During the design studio "Nature and space structures" at the Department of Architecture of the Aristotle University in Thessaloniki, Greece, explorations were taking place in parallel in both analogue

and digital media driving the design to solutions that were both aesthetically pleasing and structurally stable, so that design schemes can be further developed into an architectural artefact.

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# D1.T7.S1. COGNIZANT ARCHITECTURE - WHAT IF BUILDINGS COULD THINK?

# An Academy of Spatial Agents

## *Generating spatial configurations with deep reinforcement learning*

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*Agent-based models rely on decentralized decision making instantiated in the interactions between agents and the environment. In the context of generative design, agent-based models can enable decentralized geometric modelling, provide partial information about the generative process, and enable fine-grained interaction. However, the existing agent-based models originate from non-architectural problems and it is not straight-forward to adapt them for spatial design. To address this, we introduce a method to create custom spatial agents that can satisfy architectural requirements and support fine-grained interaction using multi-agent deep reinforcement learning (MADRL). We focus on a proof of concept where agents control spatial partitions and interact in an environment (represented as a grid) to satisfy custom goals (shape, area, adjacency, etc.). This approach uses double deep Q-network (DDQN) combined with a dynamic convolutional neural-network (DCNN). We report an experiment where trained agents generalize their knowledge to different settings, consistently explore good spatial configurations, and quickly recover from perturbations in the action selection.*

**Keywords:** *space planning, agent-based model, interactive generative systems, artificial intelligence, multi-agent deep reinforcement learning*

## INTRODUCTION

In this paper we investigate a generative model for spatial design based on learning agents, which supports fine-grained and real-time human-computer interaction.

Typically, computational agents are used for modeling natural or artificial phenomena that unfold over time based on the interactions with the shared environment (Agent-based modeling, ABM) (Wilensky and Rand, 2015). In the context of multi-agent space planning (MASP) (Veloso, Rhee and Krishnamurti, 2019), an agent can represent a spatial entity with local control, interweaving individual perception and action to decide how space should be shaped, occupied, or partitioned. The 'environment' comprehends elements of the space that are independent of the agents and that support the different interactions. During a simulation, agents receive signals from the environment, neighboring agents, or even the designer and make decisions to change the

spatial configuration. This is in contrast to many of the prevailing generative methods.

Overall, agent-based models support many characteristics that are beneficial for design exploration. They enable the control of configurations that are not feasible with a centralized modeling strategy. Agents can produce patterns or behaviors that are not necessarily predictable from the perspective of their internal programs. They operate on a shared environment and use a local action space, facilitating a fine-grained interaction with the designer. The distributed decision making of multiple spatial agents in a simulation results in partial design states with valuable information about design trade-offs and opportunities for local changes.

### *Gap in multi-agent space planning*

Agent-based models used in spatial synthesis include swarm algorithms (flocking and pheromone navigation), cellular automata, reaction-diffusion, and physics simulation (Herr and Ford, 2015; Veloso, Rhee and Krishnamurti, 2019). Cellular automata enable the emergence of patterns and has been successfully applied to conceptual form generation, urban morphology (Koenig, 2011), and even to building design (Araghi and Stouffs, 2015), but the cell-based computation imposes strict restrictions for the satisfaction of architectural requirements. Physics simulation (rigid or soft body) is a more general technique that conciliates simple control with intuitive interaction and can be adapted for different spatial problems and objectives. However, physics-based agents are reactive agents that approximately follow laws of physics. They do not have any sophisticated policy (i.e. a probability of choosing actions in every state) to manage spatial conflicts or to explore the design space. Bio-inspired models, such as swarm algorithms simulate exogenous phenomena (social navigation) in which the units can move and interact in space.

While these models enable the incorporation of certain architectural requirements, such as area or adjacency, it is usually harder to adapt them to produce conventional architectural forms or satisfy other requirements, without resorting to some form of destructive technique to improve their configurations. The challenge for agent-based, generative models is to develop control strategies that incorporate specific architectural requirements and preserve the fine granularity of the simulation.

### *Developing self-learning agents*

Reinforcement Learning (RL) is a viable alternative to develop control strategies that incorporate specific architectural requirements and to preserve the fine granularity of the simulation. With RL, agents can learn how to build spaces by interacting with the environment and improving their performance with the respect to certain goals. After training, designers can interact with the spatial agents in real-time to explore design alternatives.

In CAAD, RL has been recently applied to varied topics, such as intelligent adaptive building control (Smith and Lasch, 2016), autonomous robots (Hosmer and Tigas, 2019), fire egress evaluation (Jabi et al., 2019), and machine feedback (Xu et al., 2018). For the generation of spatial configuration, RL has been adopted for automatic decision-making with shape grammars (Ruiz-Montiel et al., 2013) and a natural selection algorithm has been used to improve the policy network of competing teams of agents that create clusters of building blocks on a grid (Narahara, 2017).

In this paper, through a proof of concept we describe an instance of our method to train agents to generate spatial configurations by interacting in an environment. We briefly describe the representation of the environment, agents, actions and objectives. Then, we focus on the description of the algorithm, which uses RL and spatial objectives provided by the designer to train the agents. Particularly, we use custom RL techniques based on deep learning for the multi-agent setting – which is referred to as multi-agent deep reinforcement learning (Nguyen, Nguyen and Nahavandi, 2018). Finally, we evaluate the performance of our proof of concept in an architectural application.

## SPATIAL REPRESENTATION OF ENVIRONMENT AND AGENTS

### *Environment and agents*

Information is organized as stacked grids of information, which we refer to as arrays. For instance, the environment is an array of shape $(d_{env}, h, w)$. The width $(w)$ and height $(h)$ define the size of the grid, and $d_{env}$ defines the number of layers of information. The basic layer of information of the environment contains two sets of cells: empty (0) and obstacle (-1). Only empty cells can be occupied by agents. More information can be added to the array as additional layers.

The agent is an array with shape $(d_{\text{agent},h,w})$. It represents a spatial partition, such as a building, a room or an area for certain activity. In this proof of concept, the spatial partition is a polyomino with no holes (PnH, see figure 1, row 1). A polyomino is a set of grid cells that share edges. By avoiding the existence of holes, the PnH has certain interesting properties. For instance, it forms a polygon with orthogonal edge boundaries and avoids containment of one agent by another. Therefore, it can form custom diagrams of floorplans, comprehending organizations such as tight packing and loose packing. The shapes can approximate any polygon, such as orthogonal and non-orthogonal rectangles, or free forms such as amoeba-like shapes. The resulting polyominoes can be post-processed to depict bubble diagrams or support the development of a parametric model. In our setting, each PnH induces different types of cells (see figure 1, row 2).

### *Action space*

The actions available to the agents are (1) single-cell expansion, (2) single-cell retraction, and (3) no-action. The set of legal cells by which the agent's expansion and retraction is defined consists of cells that are not blocked by an obstacle of the environment, preserve the PnH-ness of all the agents, and are inside the action grid. It is important to notice that the mask or action grid (see figure 1, row 3) has shape $(h_{action}, w_{action}) < (h, w)$ and is placed on the environment based on the current centroid of the agents' PnH. Therefore, as the agents expand the PnH in a certain direction, they also move the centroid and, consequently, the action grid. The basic actions are building blocks that can be combined to form complex interplays such as blocking, pushing, pulling, or attraction. For example, if the agent eliminates all the cells of its PnH using retraction, it then can jump to any legal cell inside the current action grid, using a single expansion. The agent also has the option of not executing any action this turn.

### *Spatial objectives*

Our proof of concept provides for the definition of a variety of objectives. In our first experiments, we focused on simple objectives based on neighborhood information, such as smooth adjacency, or strictly based on local information, such as area and shape – a metric that stimulates shapes with few folds, such as rectangle, L or U (for more details, see Veloso and Krishnamurti, in press). For each of these objectives, there is a utility function and a spatial representation. The utility functions $(u_{adj}, u_{area}, u_{shape})$ return a value in the unit interval representing the performance of the agent in that state with respect to a goal. The spatial functions $(g_{adj}, g_{area}, g_{shape})$ return an array with size $(h, w)$ containing spatial hints for the performance of an agent, which intends to ease training and enable parametrization by the user (see Figure 1, rows 4-6). The total utility $(u_{\text{total}})$ of an agent state is based on a combination of the selected goals.

### *A structured representation*

The state representation is composed of the different layers of information. In our proof of concept, we organized an array $(7, h, w)$ with the obstacles (environment), types of cells, utility, mask, folds $(g_{fold})$, area $(g_{area})$, and adjacency $(g_{adj})$ (see Figure 1). The organization of the state as a fixed array conditions the learning and enables the use of efficient computer vision algorithms and machine learning models.

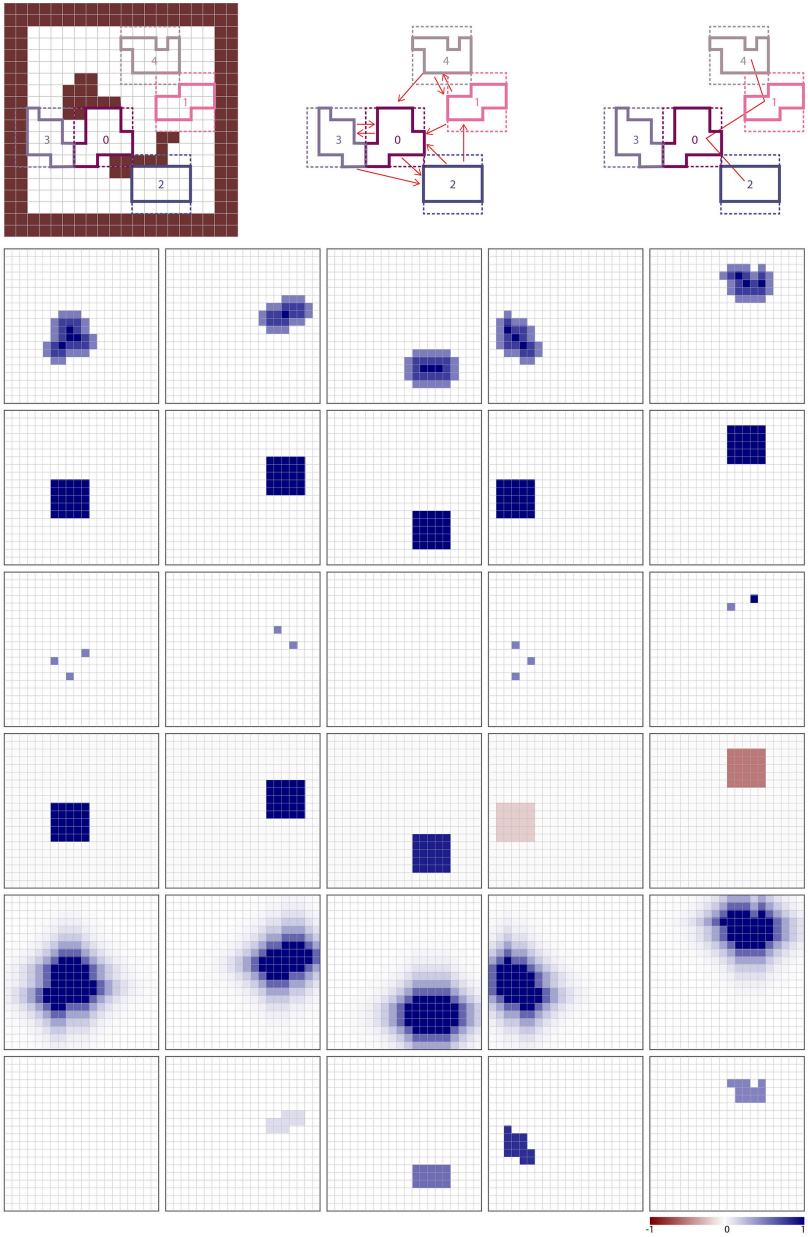



Figure 1
Row 1: left: simplified visualization of agents in the grid with obstacles; middle: closest neighbors; right: adjacency goals. Row 2: classification of the cells: structure (dark blue), surface (medium blue), and offset (light blue); row 3: mask with the action space of the agent; row 4: g_fold: indication of folding cells: L-folds (light blue), U-folds (dark blue); row 5: g_area: the agents have the respective (area/ target area): 0: (17/ 2), 1: (11/ 4), 2: (15/ 8), 3: (13/ 16), 4: (12/ 25); row 6: g_adj: soft adjacency values; row 7: the current utility of the agent (u_total) represented in the internal cells of the agent.

## LEARNING

### *Deep Reinforcement Learning*

In Reinforcement Learning, agents learn by interacting with the environment and discovering behaviors that can maximize their performance with the respect to certain goals. The mathematical framework for this interaction is a Markov decision process (MDP) (Sutton and Barto, 2018, pp. 47-57).

In our proof of concept, the MDP consists of: a set of states defined by the configuration of the agent and of the environment; a set of actions (expansions, retractions, or no-action) that can change the state of the agent; a set of reward signals based on the $\Delta$ of the combined utility functions ($u_{\text{total}}$) between two states. An agent interacts with the environment by observing its current state ($s$) and taking an action ($a$) in the MDP. The environment returns the next state ($s'$) and an evaluative feedback in the form of a reward signal ($r$).

To train our agent, we use an off-policy, model-free approach called Q-learning, which relies on estimating the future cumulative rewards for the state-action pairs (Q-values) of the MDP. The agent interacts with the environment using a policy $\pi$ derived from the Q-values estimates. Given an observation $(s, a, r, s')$, the algorithm updates the estimate $Q(s, a)$ towards a target defined by the recursive relationship between subsequent optimal Q-values in the MDP (see formula 1). This target includes a discount rate $\gamma \in [0, 1]$ to avoid infinite returns.

$$r + \gamma \max_{a'} Q(s', a') \tag{1}$$

Conventional Q-learning algorithms store every Q-value in a tabular data structure. However, to address the large state-action spaces of our setting, we estimate the Q-values using neural networks. More specifically, we use the Double Deep Q-Network algorithm (DDQN) (van Hassel, Guez and Silver, 2016). DDQN uses two similar deep neural networks ($Q_\theta$ and $Q_{\theta'}$) to estimate the Q-values.

In our version of DDQN, the agent interacts with the environment in multiple episodes, where, the objective parameters, environment values, and PnH are randomly initialized. It relies on the alternate execution of two steps: (1) interaction with the environment and (2) update of the network estimates.

In step 1, the agent interacts with the environment using an $\varepsilon$-greedy policy to generate observations $(s, a, r, s')$ – i.e. it selects a random action with $\varepsilon$ probability or an action that maximizes expected cumulative reward according to the online Q-network ($Q_\theta$) otherwise. At the beginning of a training session, $\varepsilon$ is a large value, so the policy explores random trajectories in the environment. As $\varepsilon$ is reduced over training, the agent switches to the exploitation of the best estimates. The observations are augmented with rotation and reflection, then added to a large memory buffer $D$, from which they are later retrieved for training. The buffer randomizes the data, removing the correlation between observation samples and reducing the variance for the updates.

In step 2, the algorithm updates the current estimate of $Q_\theta$ with a batch of observations $(S, A, R, S')$ retrieved from $D$. $Q_\theta$ is trained with a gradient descent method using the target:

$$R + \gamma Q_{\theta'}(S', \text{argmax}_a Q_\theta(S', a)) \tag{2}$$

Then, $Q_{\theta'}$ is slowly updated to approximate $Q_\theta$ using a step-size $\tau$, which reduces the correlation between Q estimates and target values.

### *Multi-agent deep Reinforcement Learning*

In the previous section we described the algorithm for a single agent. However, our prototype requires multi-agent deep reinforcement learning (MADRL) methods to address the problem of the interaction of multiple spatial agents that compete and cooperate to improve individual and collective rewards. In this context, the formalization of the MDP generalizes to a Markov Game, where the state contains the information of all the agents and the action space is defined by joint actions (Nguyen, Nguyen and Nahavandi, 2018, p. 10). MADRL imposes several additional challenges to RL, such as exponential growth of the joint-action space, non-stationarity due to the observation of other agents, heterogeneous agents,

partial observability, and credit assignment of global rewards.

Our approach to the multi-agent setting relies on a dynamic convolutional neural network (DCNN) to approximate the Q-values of the multiple agents. DCNN estimates the Q-values after receiving three arrays as the input:

- An array $\left(n_{\text{agents}}, 7, h, w\right)$ with the state information (see section "A structured representation").
- An array $\left(n_{\text{agents}}, m\right)$ with the indices of the m closest neighbors to reconfigure DCNN.
- An array $\left(n_{\text{agents}}, k\right)$ with the indices of the adjacent goals to reconfigure DCNN.

Each agent is represented in a strand and there are five main network blocks (see Figure 2).

Over the sequence of blocks, the network captures a larger and larger receptive field, defined by neighbors and neighbors of neighbors. The strands of the network for each agent not only share weights but also gradients. Therefore, the backpropagation step of DDQN enables cooperative adjustment of weights between agents. As a result, while the number of closest neighbors (m) and maximum connected agents (k) should be fixed, the number of agents in the model can be changed during execution, by adding or removing strands.

The first block receives the state array of each agent and uses a convolutional neural network to create a richer representation. The second and third block use convolutional neural networks on the resulting arrays of the closest neighbors and connected agents. The fourth block uses a convolutional neural network on the combination of the resulting arrays from previous blocks. Finally, the fifth block is a Q-network that receives the resulting array from the previous block associated with the mask of the agents and computes the respective Q-values using fully connected layers.

## EXPERIMENT

| | | | |
|---|---|---|---|
| **env. grid** | 16 x 16 (w/padding) | **loss function** | Smooth L1 Loss |
| **action grid** | 5 x 5 | **optimizer** | RMSProp |
| **actions space** | 26 | **batch size** | 64 |
| **n of agents** | 6 | **learning rate (α)** | 0.0001 |
| **adacencies (k)** | 3 | **τ** | 0.02 |
| **neighbors (m)** | 3 | **capacity of D** | 10000 |
| **episodes** | 43350 | **initial** ε | 0.9 |
| **steps per episode** | 64 | **minimum** ε | 0.1 |
| **γ** | 0.92 | ε **reduction** | custom schedule |

Table 1
Configuration of training.

Our approach to interactive generative design is to train spatial agents that build custom spatial configurations and adapt to changes devised by real-time interactions with the designer. This interaction includes not only changes in the parameters of the simulation (ex: number of agents, area, adjacency, and amount of randomness in action selection) but also direct changes to the PnH configuration of the agents and of the environment.

In this section, we report an experiment that evaluates the quality of the spaces generated by the agents, and their capacity to generalize their knowledge to unknown situations and to react to perturbations in the cell configuration.

In the training setting (see Table 1), six agents are randomly initialized and interact in randomly generated environments during multiple episodes of 64 steps. The reward signals are derived from the following utility function:

$$u_{\text{total}} = 0.5u_{adj}(u_{area} + u_{shape}) \quad (3)$$

In the experimental setting we use twelve agents to represent the spaces of a generic two-bedroom house (see Figure 3). There are two custom environments: a terrain on the top of a hill with irregular boundaries and a terrain with a bridge over a stream. For each environment, the agents interact for 6500 steps, which are divided in three stages that are separated by two phases of perturbations:

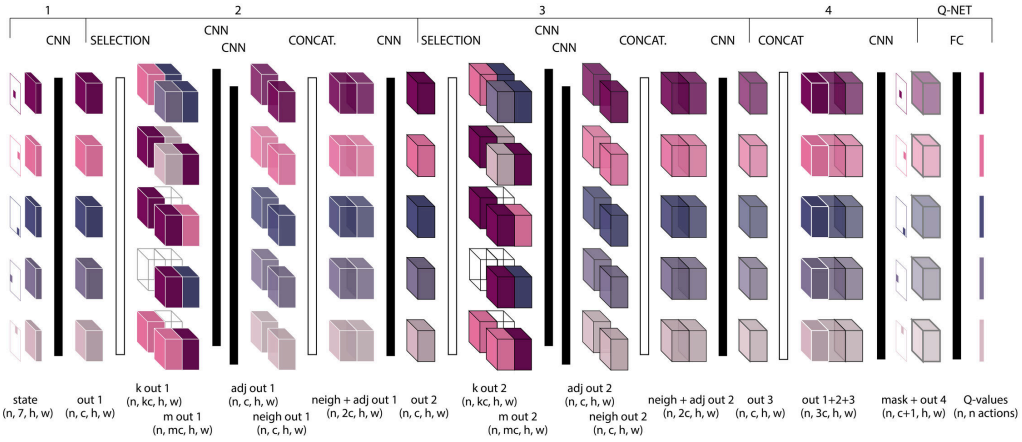



Figure 2
Simplified graphical representation of the layers, operations, and arrays of DCNN. Every CNN is composed of 2 convolutional layers with 64 filters of size 3x3, stride 1, padding 1 and a Leaky ReLU activation. The final FC network has 3 linear layers with 104, 52, and 26 neurons. Its two first layers use Leaky ReLU activation, while the last uses a hyperbolic tangent function (Tanh).

- Stage 1 (0-1999): the agents start at random positions and use the learned policy 95% of the time and random actions 5% of the time – i.e. $\varepsilon$-greedy policy with $\varepsilon = 0.05$.
- Perturbation 1 (2000-2099): actions are selected randomly.
- Stage 2 (2100-3099): agents use an epsilon greedy policy with $\varepsilon = 0.05$.

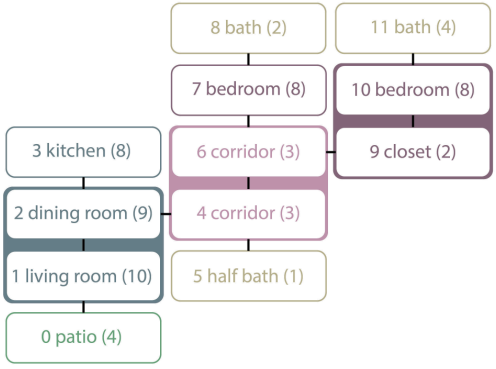



Figure 3
Program of the house for the experiment. The leading number is used to identify the spaces in the next images. The numbers in parenthesis indicate area. The connections indicate adjacency. The colored grouping indicates spatial integration between spaces.

- Perturbation 2 (3100-3499): actions are selected randomly.
- Stage 3 (3500-6499): agents use an epsilon greedy policy with $\varepsilon = 0.05$.

The cell configuration of the obstacles and agents is the input of a parametric model which generates the geometry for visualization, with floors, walls, windows, and openings for doors. The openings are inserted randomly in the intersection between adjacent environments. The windows are inserted in one of the external edges of the PnH (bedrooms and kitchens) or in one of the external edges of a cell of the PnH (bathrooms). Some partitions are integrated to create open spaces, such as in the dining and living room or in the bedroom and closet. The social spaces have glass walls, the patio does not have any walls, and the remaining spaces have walls on the edges without doors or windows.

Figure 4 and Figure 5 show some snapshots of the resulting configuration for the two environments over 6500 steps. The agents generated multiple configurations with high scores and adapted to the obstacles. Overall, the agents improved the performance of the global configuration either from random initialization or from a random perturbation in all the scenarios. After the perturbations, the agents were able to re-organize in different spatial configurations, which shows the potential for direct interaction with the designer. Also, interesting adaptive spatial patterns that were not part of the objectives emerge from the interaction of the agents with local

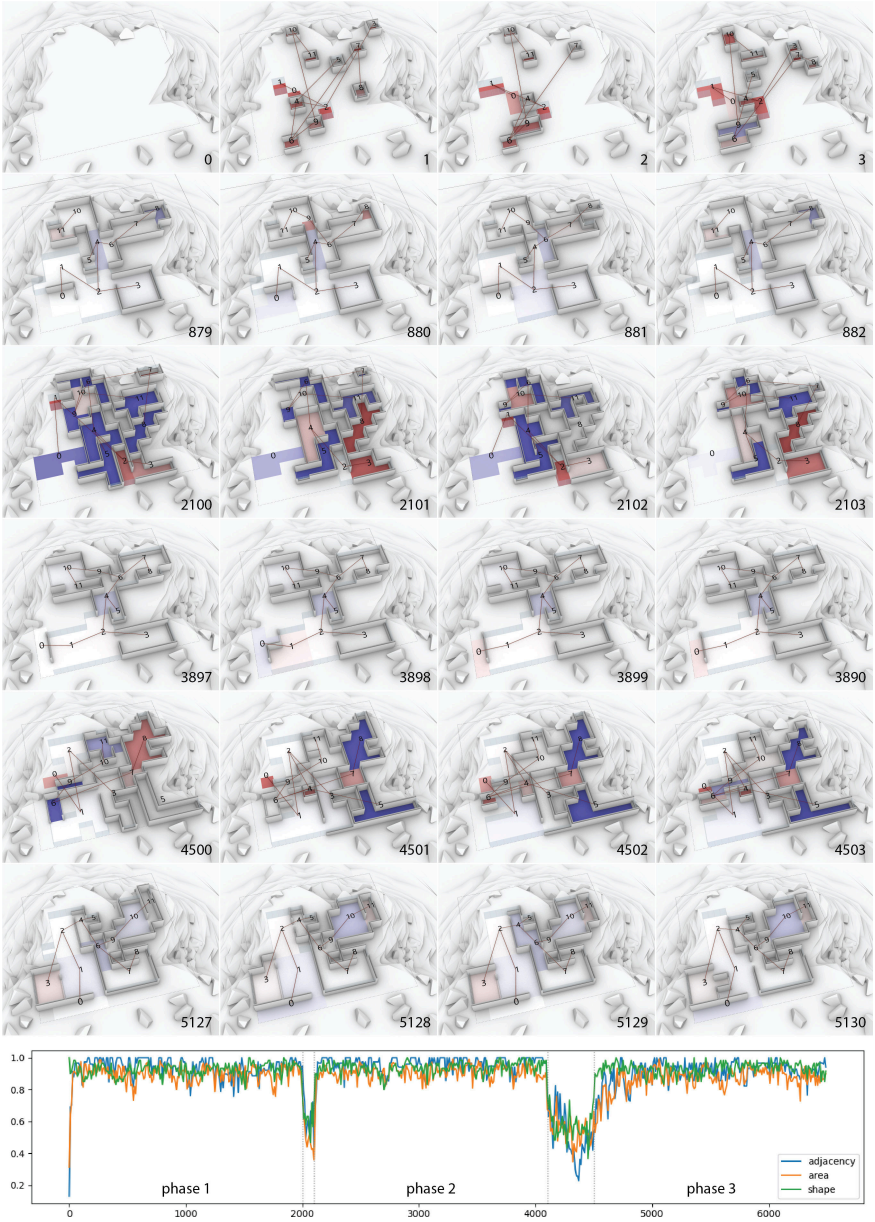
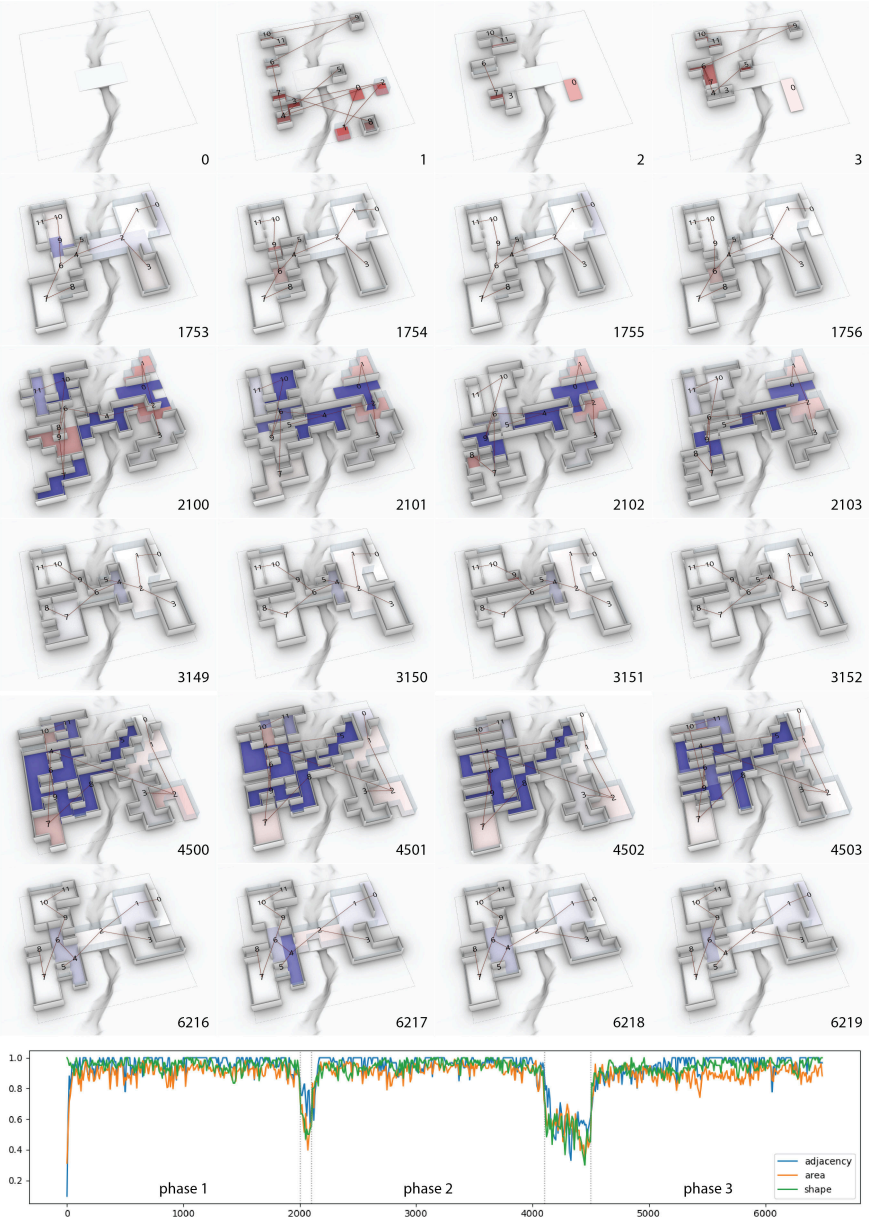



Figure 4
Rows 1-6: simulation of 12 agents in a terrain on the top of a hill with irregular boundaries. Every pair of rows contain the first 4 steps in a stage of the simulation and 4 steps selected visually. Row 7: graph with the average performance of the agents (y axis) over the episode (x axis). The areas between dotted lines indicate the periods where action was selected randomly (perturbation).

Figure 5
Rows 1-6: simulation of 12 agents in a terrain with a bridge over a stream. Every pair of rows contain the first 4 steps in a stage of the simulation and 4 steps selected visually. Row 7: graph with the average performance of the agents (y axis) over the episode (x axis). The areas between dotted lines indicate the periods where action was selected randomly (perturbation).



situations. For example, an agent created a protuberance to increase the area and to adapt to local obstacles (Figure 4, patio at 3898 or kitchen at 5128) or a small courtyard emerged between the sectors of the house (Figure 5, at 6216, and 6219).

## CONCLUSION

In this paper, we introduced a workflow to train agents for spatial diagramming and planning. The agents successfully learned how to generate spaces, addressed specific spatial goals, preserved fine-grained interaction with the representation and were able to react to perturbations in the simulation. This algorithm will be improved and integrated to a game engine, so designers can use custom tools to interact with the model by changing parameters of the simulation and the PnH configurations of the environment and agents in real-time. By promoting the conversation between computational agents and the designer, we expect to support improvisation and cyclic reasoning in generative design.

## ACKNOWLEDGMENT

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# Towards an Interactionist Model of Cognizant Architecture

## *A sentient maze built with swarm intelligence*

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*Cognizant Architecture is a term used to define sentient and smart structures broadly. In this paper, an `Interactionist' model of cognizant architecture is proposed as a method of investigating the development process by inverting the conventional concept of maze design. The proposed `Cognizant Maze' aims to achieve user-architecture micro-interactions through delighting the users, presenting a physical activity equally attractive to kids and adults alike, and activating mind-enticing visual effects. Like many previous innovations, nature is what inspires us in the maze-making process. In modelling the cognizant maze, we develop the concept and workflow of prototyping a form of swarm intelligence. We are particularly interested in exploring how simulated behaviours of swarm intelligence can be manifested in a maze environment for micro-interactions to take place. Combining parametric modelling and Arduino-based physical computing, our current interactive prototyping shows how the maze and its users can `think, act and play' with each other, hence achieving an interactionist model of cognizant architecture. We reflect that the lessons learned from the Cognizant Maze experiment may lead to further development of cognizant architecture as a propagation of swarm intelligence through multi-layered micro-interactions.*

**Keywords:** *swarm intelligence, maze design, Micro-interactions, interactive prototyping, cognizant architecture*

## INTRODUCTION

Cognizant Architecture is an endeavour of designing and realising built structures that can 'think and act' for themselves. The recent technological advancements have opened up many avenues to transform architecture into sentient systems. Given this, the traditional concept of maze design is challenged in this paper by programming an interactionist model that acts in response to human movements and activities. The interactionist model introduced a new dimension to the design of labyrinths that have evolved over 4,000 years (Wilson, 2018). The social life of peo-

ple nowadays consists primarily of electronically mediated relationships. Instilling any curiosity in the minds deeply linked to the digital world can only be achieved by challenging it with structures that they think for themselves (Scheer, David R. 2014).

Labyrinth generation is a process of constructing the layout of passages and walls within a maze. As an interactive puzzle, maze contains every branch of a tree in graph theory, which stands for a route out to perplex the human intellect and psyche. Since long, mazes have acted like places where players could have fun by unravelling puzzles. However, the problem lies in the fact that once solved, the interest element of a typical maze decreases to virtually zero. To conquer this flaw, the project has been developed in a way that uses a unit panel model and unites it with Artificial Intelligence (AI) techniques to create a maze that retains entertainment value like a game of chess.The challenge in achieving this design is developing a configurable system that would detect the player's movements through the maze and deploy offensive strategies to counterattack their decisions. This paper shows the three steps involved in the formation of the cognizant maze.

- Designing a simple modular labyrinth system for ease of production.
- Programming motions for various units based on swarm intelligence techniques.
- Making the entire system intelligent using Arduino techniques.

## SWARM INTELLIGENCE

Joanna Kwiecie (2018) in her article describes a swarm intelligence system as: "A coordination system of a group of individuals, being a decentralised system, composed of autonomous units, is responsible for the organisation of tasks required for resolving a specific problem." This concept has been widely employed in work on artificial intelligence. The expression was introduced earlier by Gerardo Beni and Jing Wang in 1989; in the context of cellular robotic systems.

In general, swarm intelligence describes the ability of the individual members to perceive their surroundings to the overall flock behaviour. To date, substantial research on modelling swarm intelligence has been carried out, and several computational design strategies have been developed (Sebastian, W., 2016). These studies were based on replicating the collective behaviours of a group of birds, or insects or a herd of mammals working together to achieve a common objective. As shown in Figure 1, the best example of these actions is seen in the flock's evasion from a predator.

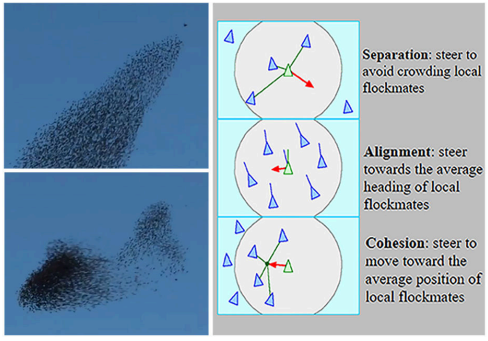



Figure 1
Behaviour of a starling swarm when a predator approaches and it's analysis.

Again, according to Kwiecie, "Most often, swarm intelligence is used to resolve the issues relating to optimisations, finding best routes, assignments, developing work schedules, task arrangement or object grouping. However, the complete natural systems seem to be reliable and fitted with the capability of adaptation to environmental changes." For this project, relationships developed during the movements have been studied, and principles learned form a baseline for the concept development. Gathering information from the immediate surrounding and transferring a stimulus based on the information through the entire flock is the simple principle used by these entities [Figure 2: Zaleshina, (2019)]. The whole phenomenon can be broken down into four simple rules:

- Following neighbor's direction of movement
- Remaining close while maintain distance from neighbor
- Acting as individual entities
- Transmitting signals in case of need.

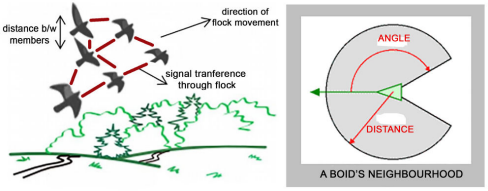



Figure 2
Boid's distances and rules.

## AN INTERACTIONIST MODEL

To contextualise swarm intelligence in architecture, we adopt an Interactionist approach to modelling human-microenvironment interactions. Symbolic architectural interaction is an offshoot of architecture sociology that gives us a frame for designing a physical environment intertwined with human persons, with one potentially influencing and finding expression in the other (Ronald W. Smith, 2001). Involving computer programming in the design of spaces that interact with users is not new. In 1967, Nicholas Negroponte founded the Architecture Machine Group at MIT, a lab and a think tank whose members studied new approaches to human-computer interaction (Tristan, 2005). In the sections below, we present steps of prototyping a cognizant architecture that interacts with the player, using maze design as a testing ground.

## PROTOTYPING A COGNIZANT MAZE (STEP I): PARAMETRIC MODELLING

### *Concept*

Unlike a typical hedge maze in a park, for this sentient game, we propose a parametrically designed installation [Figure 3]. The model comprises of three main components, the support posts, the blades, and the horizontal bars that attach the blades to posts. Each blade is treated as a boid programmed to follow swarm intelligence behaviour. It not only acts independently but also assembles to execute the required objective. These blade components mimic birds that horde together like a flock, generating panels. The base form for the installation is two concentric spirals. These spirals are divided in a manner that the unit size of the blade remains constant. The number of modules in each panel depends on the height of the support posts. The panels are then divided into groups depending on the type of motion they would perform. Finally, each panel group is coded to conduct their movements. By acting in reaction to the decisions made by the person (player), the maze provides a personalised experience for each player.

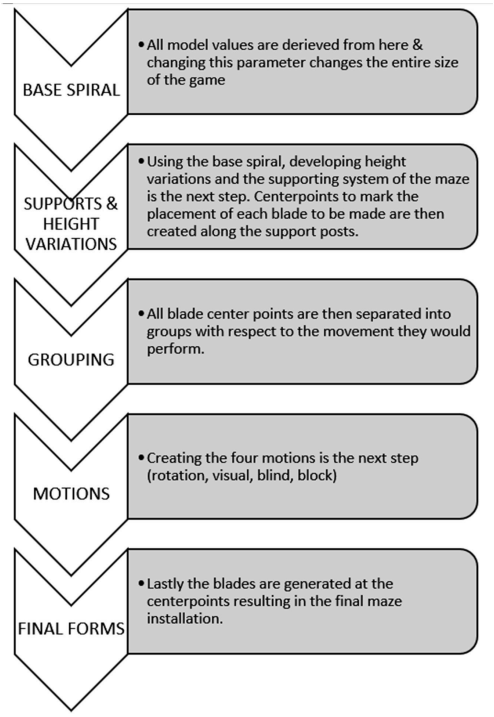



Figure 3
The parametric modular development process of the maze design.

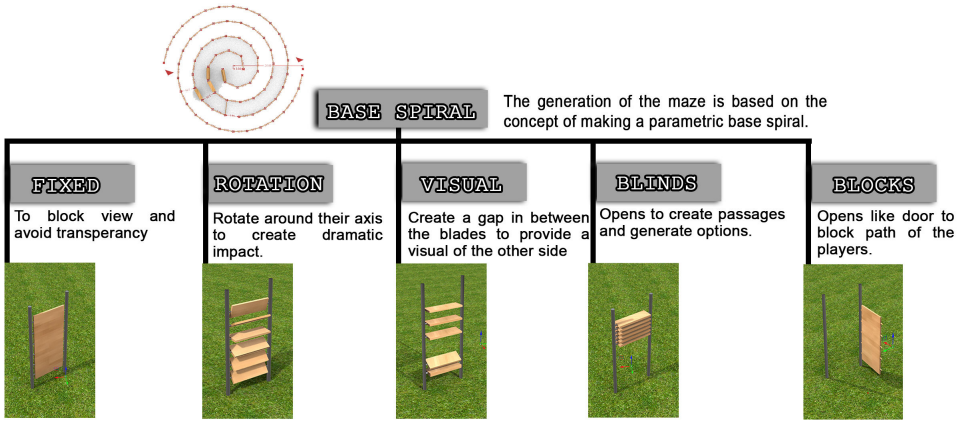



Figure 4
Implementation of five types of panels motions to the base spiral to manifest the impact of simulated swarm intelligence.

Since all blades of the labyrinth are configured with simulated swarm intelligence behaviours, each panel not only acts as a part of a stable wall to create isolation and but also senses the player's movements [Figure 4].

By calculating the individual's distances from the panels, the panel movements can be activated to operate in different ways to trap, make way or create diversions. The movements are captured by motion sensors, which are analysed to perform specific activations. As a result, the paths in the maze will be changing along with the different decisions made by each player, making it an interactive and intelligent installation.

### *Implementation*

The movement generation in the panels is implemented by dividing into five different groups (fixed, rotation, visual, blinds and block panels) [Figure 4]. As shown in Figure 5, each group is programmed to perform a specific movement. Like birds in a flock, the panels can act independently ( like the rotation, visual and fixed panels) or collaborate with others (like the blocks and the blinds). The fixed panels always stay still and maintain the mystery of the maze by creating visual blocks. The dramatic impact of swarm intelligence is created by the rotation panels when rotating randomly around their axes in response to sensed human motions. The visual panels, on the other hand, create a gap at eye level height by separating themselves into two different groups moving up and down along the vertical post. Blinds panels not only open as a door to create a new path when a player approaches them (generating options to confuse the player) but also pass the signal to the nearest block panel and activate it to block the player's path. With the five types of panels working together, the maze gains the ability to act cognitively and simulate human intelligence resulting in a dynamic and interactive game.

Figure 5
Panels composed of blades configured with simulated swarm intelligence behaviours reacting to people approaching.

## PROTOTYPING A COGNIZANT MAZE (STEP II): VIRTUAL GAMING

Based on the parametric modelling in Step I, we develop a rule-based virtual gaming system for testing the maze's swarm intelligence behaviours. Much like evading a predator, the swarm of panels is pro-

grammed with a set of rules that lures people towards the centre of the maze using shortcuts. If the player's distance from each panel is less than the assigned value a stimulus is generated indicating the member to perform the necessary motion.

Figure 6
Shortest distance towards the center.

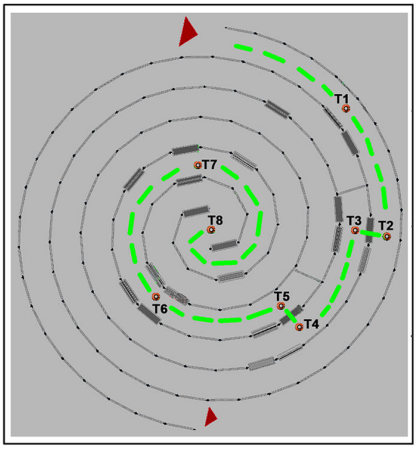
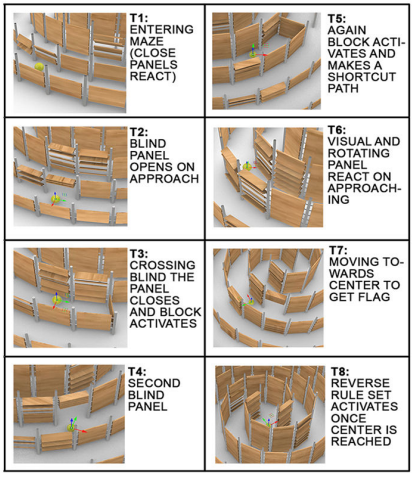
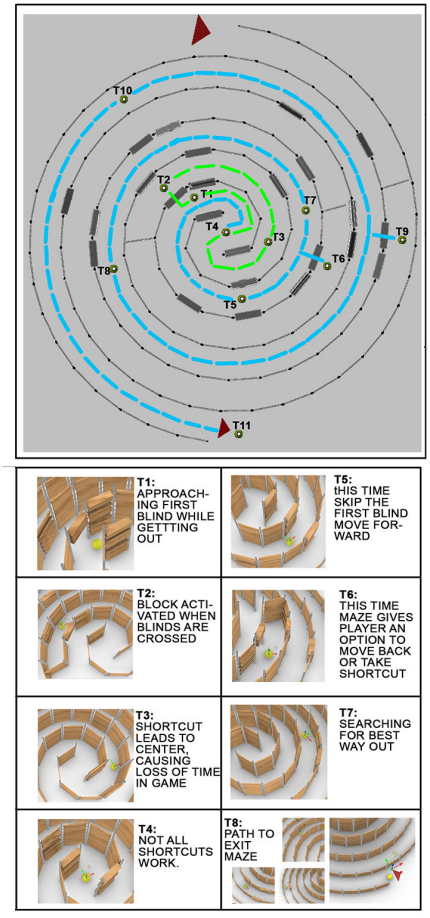



Figure 7
Looping back to center and creating misdirection when getting out of the maze.




In some instances, the components react to the other members in the swarm to block paths and compel players to move in the desired direction as depicted in the images in Figure 6. But once the player reaches the centre, the initial set of rules are changed. Now the maze will open up misdirecting shortcuts that will loop back to the centre, making it difficult to solve the puzzle (shown in the green path in Figure 7). In this case, the player has to figure out the right way while the panels keep reacting to the player's choices to fabricate hindrances along the path. Some of the blind panels are designed to remain open for a while to allow the person to rethink their decisions. One path could be to follow the spiral without interacting with the maze (but it might not be the fastest path).



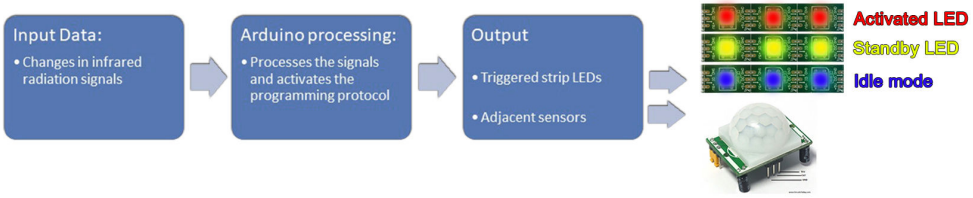



Figure 8
Arduino prototyping process and coding behaviours.

## PROTOTYPING A COGNIZANT MAZE (STEP III): ARDUINO-BASED SIMULATION

### *Components*

The third stage of the project resulted in making prototype simulation using digital design with Arduino sensor and actuator techniques to generate cognizant architecture behaviours.

To achieve this objective, we made the decision to use PIR (passive infrared) sensors in the project. Once the object in its view moves, it generates signals that can be taken as input parameters in Arduino. The PIR sensors are ideal for detecting movements. The second component used in the simulation is the programmable RGB LED strips. These are adaptable LED that can be linked to Arduino control boards to produce a wide range of colour variations. Each LED light on the strip represents one panel of the virtual maze game-[Figure 8].

### *Assembly & testing*

The base for the prototype is a wooden disc with punctures at various points that open into the spaces below. The sensors are placed in these pits, and the depth provided helps to control the sensor's wide-angle view. This also helps to reduce the interference between adjacent PIRs. The plate is supported by the PIR cavity tunnels that have been punctured at places to allow convenient workings of the wiring connecting to the main Arduino board. The LED strips are then arranged in the form of two spirals, as shown in Figure 9.

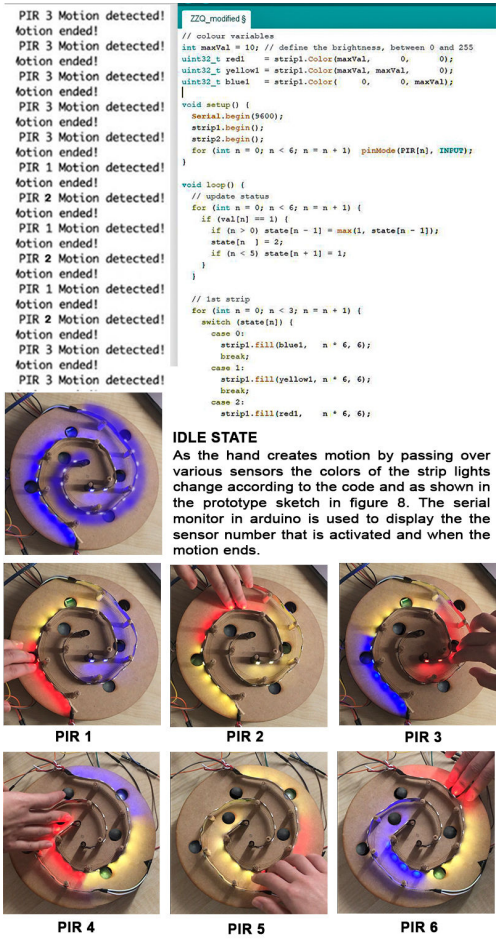
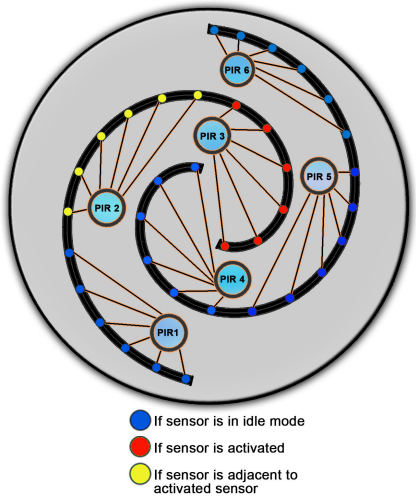



Figure 9
Assembled prototype model workings.

Figure 10
Simulation sketch.




Each motion detector is then connected to 6 RGB LED lights. Once a motion is detected by variations in infrared radiations, a signal is sent to be processed through the Arduino code [ Figure 10]. It is here that the program sends signals to the 6 LEDs attached to the triggered PIR sensor to turn red (representing an activated state). Like the transference of stimulus through the body of a swarm of birds, a warning signal is sent to the neighbouring sensors. As a result, they trigger the lights attached to them to turn yellow (standby state). Through Arduino programming, the person's exact location in the maze can be pinpointed, and the panels closest to the person can react while the adjacent panels are also activated accordingly. In this way, the labyrinth reacts cognitively to the decisions made by the player.

## CONCLUSION

In this paper, we have demonstrated how swarm intelligence observed in nature can be applied in the design of a cognizant maze that may delight the human psyche and intellect. The depth and complexity of a typical maze are enhanced by tracking the individual's movements and the cognizant ability of each Boid. We show a model of cognitive & responsive architectural components that can adapt to changing patterns of user decisions. The modular algorithm implemented allows maze design to produce a variety of sizes in the most simplified manner, as shown in the on-site rendering of a medium-sized maze in Figure 11 and 12.

The swarm of panels developed thus far interact with the players through their movements. Further progress in this direction would involve learning from the player's action and deploying responsive strategies accordingly. It should be noted that the design developed until now is based on a modular unit that can only perform one type of motion. But, the panel design can be evolved to perform the five different movements depending on the situation. By doing so, the maze's cognizant abilities can be significantly enhanced, resulting in more choices for each decision made by the player.

Based on the algorithms developed for the Cognizant Maze, it would be interesting to see real-time swarm intelligence in action. For example, generating a louvred facade system that makes use of weather sensors and the Internet of Thing (IoT) to intelligently maintain comfortable interiors, or creating efficient evacuation routes in a building by propagating detected stimulus through a swarm of opening/closing building components. There could be many other applications of this remarkable natural phenomenon.

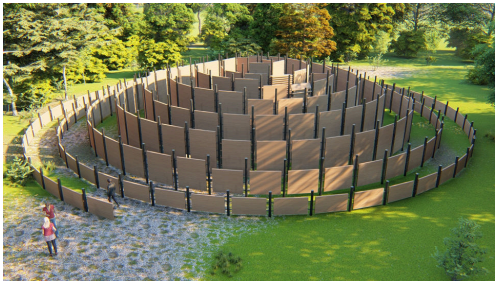


Figure 11
Rendering of a medium-sized maze in a park setting.

Figure 12
Eye-level view of the maze in the park setting.

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# Documentation and Analysis of a Medieval Tracing Floor Using Photogrammetry, Reflectance Transformation Imaging and Laser Scanning

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*[1,2,3,4,5]{njwebb|James.Hillson|jrp|alexb|smduffy}@liverpool.ac.uk*

*The fifteenth-century tracing floor at Wells cathedral is an extremely rare survival in European architecture. Located in the roof space above the north porch, this plaster floor was used as a drawing and design tool by medieval masons, the lines and arcs inscribed into its surface enabling them to explore their ideas on a 1:1 scale. Many of these marks are difficult to see with the naked eye and existing studies of its geometry are reliant on manual retracing of its lines. This paper showcases the potential of digital surveying and analytical tools, namely photogrammetry, reflectance transformation imaging (RTI) and laser scanning, to extend our knowledge of the tracing floor and its use in the cathedral. It begins by comparing the recording processes and outputs of all three techniques, followed by a description of the digital retracing of the tracing floor to highlight lines and arcs on the surface. Finally, it compares these with digital surveys of the architecture of the cathedral cloister.*

**Keywords:** *digital heritage, photogrammetry, reflectance transformation imaging, laser scanning, medieval design*

## INTRODUCTION

As a team of researchers at the University of Liverpool, we are investigating the design and construction of English medieval vaulted ceilings. A central aim of the project is to understand the design processes used by medieval masons, with one of our case study sites being Wells cathedral. Our main method to achieve this is to produce a laser scan survey of church and cathedral interiors. This 3D data is then processed in order to extract the underlying geometry of individual vault ribs, allowing us to reverse engineer their design process. However, in order to test our understanding of medieval design practices it is necessary to explore evidence besides the built vault fabric, and a prime asset for this is the surviving tracing floor at Wells.

The tracing floor is a level, 5.5 x 6.5m plaster surface located in the roof space above the north porch (figure 1). Here the masons inscribed lines and arcs into the plaster to investigate design ideas prior to construction. The tracing floor has previously been documented using analogue techniques, notably by Colchester and Harvey (1974) and Pacey (2007). However, digital surveying and analysis tools have the po-

tential to uncover elements that are difficult to see by eye, which we explore in this paper. Once the digital survey process is completed, this also gives us an opportunity to compare the geometry found on the tracing floor with that used in the cathedral's vaults, in particular the apparent match with the cloister's east walk (figure 2) which was previously observed by Pacey (2007). Our research therefore takes a reverse approach to architectural design today, working not from digital designs to material fabric, but instead from material fabric to digital versions. In this way we can document and analyse existing works of architecture, in particular their design processes, using advanced digital methods.

Figure 1
Wells tracing floor, where inscribed lines can be seen on the surface.

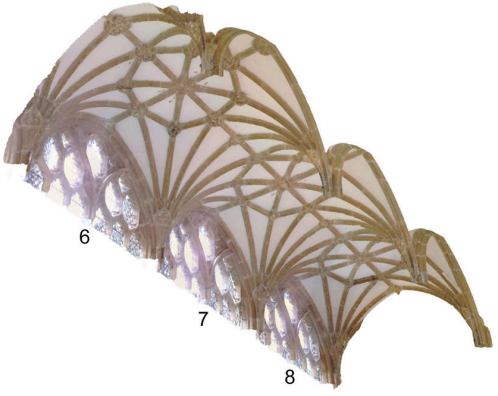


Figure 2
Mesh model of the east cloister vaults at Wells cathedral (bays 6-8, numbered N-S).

This paper will first document the three methods used to record the tracing floor: photogrammetry, reflectance transformation imaging (RTI), and laser scanning. Then it will discuss the respective strengths and weaknesses of each method based on their digital outputs. Next it will relate the process of digitally retracing the incised lines and arcs which these outputs have revealed on the tracing floor's surface. Lastly, it will briefly discuss the digital methods used to survey and analyse the vaults in the cathedral cloister, comparing our hypothesis for their 2D and 3D design processes to the geometry found on the tracing floor.

## METHODOLOGY

Our survey of the tracing floor had to be precise in order for any comparison with the cathedral's fabric to be meaningful. Consequently, we decided to test three methods to ensure comparative accuracy. This also gave us the opportunity to compare each digital surveying method and their respective outputs. Protecting the floor itself was of the utmost importance and we strategized carefully to avoid damaging the plaster surface. Equipment was either hung from roof joists above or positioned on carpet tiles laid over the floor. The latter also acted as a useful surveying grid.

### *Photogrammetry*

The first method which we used to record the tracing floor was photogrammetry, a process where hundreds of digital photographs were taken on site and composited together using Agisoft Metashape to create a full 3D digital model. We have previously undertaken detailed analysis of photogrammetry as a method to survey vaulted ceilings, finding the technique to be inadequate, as the distance between the camera and subject was too great to give a level of detail meaningful for analytical purposes. Consequently, we opted for laser scanning as our standard method (Webb et al. 2016). The tracing floor, by contrast, can be photographed at close range and photogrammetry therefore has much greater potential for capturing fine details. This can be seen in

comparative projects such photogrammetric imaging of a large-scale Diego Rivera fresco mural, enabling an accurate record of it in 2D as well as fine 3D details such as the layering of paint (Schroer et al. 2018). The project, however, acknowledges the issues of data processing over 1500 photographs taken with a 50-megapixel high resolution camera. Similarly, Guidi et al. (2014) were able to survey at depths of around 1mm to capture inscriptions on a historic temple using photogrammetry, and acknowledged it was uncertain whether a laser scanned equivalent could achieve the same detail. Precedent therefore suggested photogrammetry as our first choice for the tracing floor survey. For our experiment, hundreds of digital photographs of the floor were taken systematically in four stages using a Sony A7 Mk3 camera:

- First stage: photographs taken at an oblique angle looking across the floor, with a 24mm focal length.
- Second stage: photographs taken with a wide angle looking straight down at the floor to record the wider context, with a 24mm focal length at a distance of 1.4m.
- Third stage: photographs taken from a narrow angle looking straight down to the floor to record detail, with a 50mm focal length at a distance of 1.2m.
- Fourth stage: photographs taken from a narrow angle with a slightly oblique view towards the floor's edges to record any missing detail, with a 50mm focal length at a distance of 1.2m.

The roof joists in the space containing the tracing floor are below head height, which made precise positioning of the camera difficult on some occasions (figure 1). On the other hand, they also provided useful supports for an opened tripod with the camera pointing downwards, as well as a linear sequence which we could follow to ensure all details were captured. The space has no artificial lighting and the only natural light enters from a single north-facing window. In daylight this provides good ambient light to the north of the tracing floor. However, the light gets gradually poorer the towards the south side of the floor (approximately 1/10 the brightness in the south compared to the north), requiring two flash guns to be used to balance the lighting conditions.

Once we were satisfied that we had enough photographs, these were composited together using Agisoft Metashape, which utilises perspective differences between images to evaluate the floor and the surrounding scene's geometry. A full 3D digital model was then produced in point cloud form, which was converted to a mesh model and orthorectified images as required. Whilst the 3D model did highlight some of the deeper scratches on the floor's surface, it was the orthorectified images that proved to be the most useful in identifying incised lines and arcs, provided that they were exported at a sufficiently high resolution: 0.25mm per pixel giving a total image size of over 500 megapixels. Though we experimented with using the mesh model, we found that tracing the orthomosaics using conventional drafting software was faster, more accurate and yielded more satisfactory results. The orthomosaics were not without problems though, the main issue being variable image quality across the surface, namely pixilation and changing lighting conditions. This meant that it was impossible to come up with a uniform way of identifying lines and arcs, which had to be performed on a case by case basis.

Whilst the photogrammetric survey enabled us to view the floor orthographically, it did not necessarily offer anything new compared to previous surveys completed with analogue techniques. The main difference between these analogue methods and our photogrammetric survey is the potential for human error: the digital tracing floor orthomosaics are much less likely to include mistakes in the recording process, as they are based on orthorectified photography, removing distortions potentially apparent in the previous analogue survey. Additionally, detailed recording could be made at a computer screen, rather than in-situ in the roof space of a cathedral, which has limitations. However, ideally one would do both, enabling checking against reality during the

identification and recording process. Very fine lines, sometimes under 0.25mm wide/deep, were also difficult to record accurately (but less problematic for wider and/or deeper marks), and it generally was not possible to establish line depth. Nevertheless, the photogrammetry orthomosaics will provide an accurate digital record for researchers to use in the future (figure 3).

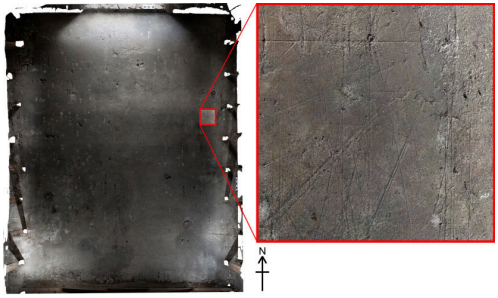


Figure 3
Orthomosaic of the tracing floor created using photogrammetry.

### *Reflectance transformation imaging*

The second method we investigated to help uncover the secrets of the tracing floor was RTI photography, which has the potential to reveal details that are difficult to see by eye or with photogrammetry. This involved taking multiple images from a static location, but lit from different angles. The results were processed in software to create a synthetically relightable image where users can light a target area from any direction. This can simulate the effects of raking light, bringing out very fine marks and surface textures, and has previously been used mainly in the field of archaeology (Mytum et al. 2019).

Photographs were taken again using a Sony A7 Mk3 camera, rigidly mounted in a static position looking directly downwards at a target area of the tracing floor (approximately 400x300mm). Each image needs included a scale bar and two reflective spheres, similar to but larger than metal ball bearings. The distance of the target area was measured corner-to-corner, in this case approximately 500mm, then multiplied by four (approximately 2000mm) giving the ideal distance from the target to the light source: a hand held flash gun. Maintaining a consistent distance is essential to avoid variation within an image set, this is done using a piece of string of the right length. Placing the flash gun at this distance reduces the effects of parallax in the lighting whilst still ensuring it is close enough for the flash to be effective. For some image sets the distance had to be reduced to 1500mm due to obstacles. Next, the flash brightness was tested for correct exposure and the flash power adjusted as necessary. The camera was set to a low ISO with a moderate aperture (f8) and a fast shutter speed (1/200). Once this setup was completed, a set of photographs were taken as the flash gun was repositioned across a 2000mm hemisphere over the target. Photographs were taken with the flash positioned every 45 degrees in plan (8 groups of images) and every 15 degrees vertically (5 images per group), with some intermediary images giving around 60 photographs in total which record the exact same target area lit from different angles by a stable light source (figure 4).

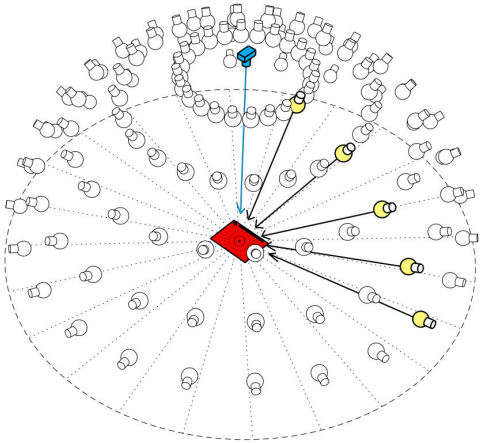

Figure 4
Example diagram of hemisphere setup, showing the target area (red), camera (blue) and light sources, showing a vertical run (yellow).

The process of surveying the tracing floor using RTI was relatively straightforward, the main exception being working on a target area close to the edge where the pitched roof and its supports made some photographs difficult to capture. The other issue was

only being able to capture an area of approximately 400x300mm due to the camera resolution and flash distance requirements described above. The recording of each target area took around 25 minutes and we only had limited access to the floor because of guest tours operated by the cathedral, for which the tracing floor is a central attraction. Therefore, we were only able to record part of the floor using RTI, instead prioritising the completion of a full photogrammetric survey as well as laser scanning.

Once all target areas were photographed, the photograph sets were processed using RTI Builder, software developed by a team at the Universidade do Minho [1]. Images were first transferred from the camera to a computer and converted from RAW to JPEG format. Each individual image was checked for errors, with problematic ones removed, then all remaining images were loaded into RTI Builder. Next, the area of each image containing the reflective spheres was selected, and using this, highlights from the light source could be automatically detected to determine light source direction. The RTI model was then built using Polynomial Texture Mapping (PTM) fitter, using a HP Labs algorithm. Next the model was checked for errors and the tracing floor surface was explored using RTI Viewer. Here, the direction of light is adjustable in order to highlight surface texture detail. Different rendering modes were explored to ensure as much surface texture as possible could be viewed. The most useful ones were 'default', which tries to faithfully represent the object under directional lighting conditions, 'specular enhancement', where the floor surface appears to be wet giving a reflective surface sheen (colour can also be disregarded here as at times it can be distracting), as well as 'normals visualisation', a single static image with no adjustments, where normal vectors are rendered as colours (figure 5).

### *Laser scanning*

Our third survey method was laser scanning, which we tested for both the tracing floor as well as the cathedral and cloister vaults. We used a Faro S 150 and for the tracing floor survey selected its highest settings of 1/1 resolution and 8x quality, giving a scan time of two hours and a resulting point cloud of over 20 million points. We wanted to see whether the laser survey could record the lines and curves of the plaster surface using these settings. We only had time to produce a single scan for this test and additional scans would likely have helped to produce a better 3D model. However, it is unlikely that this would have had a major impact on the recording of lines and arcs on the tracing floor surface, as they are often too fine to be detected by laser scanning.

Once processed, we produced a both a 3D mesh model and point cloud to interrogate the tracing floor surface. The results were poor even at the highest settings, with individual scratches on the plaster surface being very difficult to see, except for some of the larger ones. A similar experiment by Guidi et. al. (2014) produced better results, however, their target object had much greater surface undulations than the tracing floor. The photography and resulting orthophoto of the tracing floor, however, was better than expected, yet were still not as clear as the results from photogrammetry. Consequently, we focussed our tracing floor findings on the photogrammetry and RTI outputs. Nevertheless, laser scanning provided an excellent method of capturing the ge-

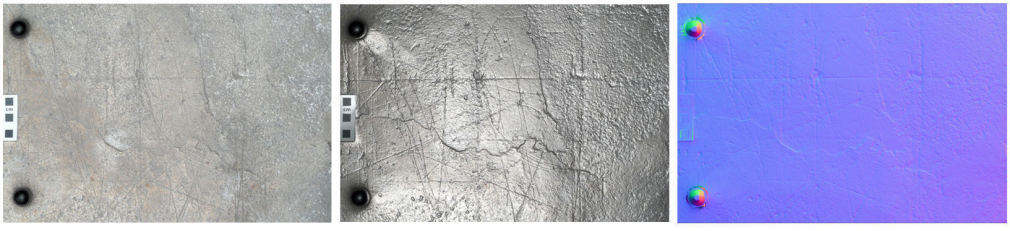

Figure 5
Processed images in RTI Viewer showing 'default' (left), 'specular enhancement' (middle) and 'normals visualisation' (right).

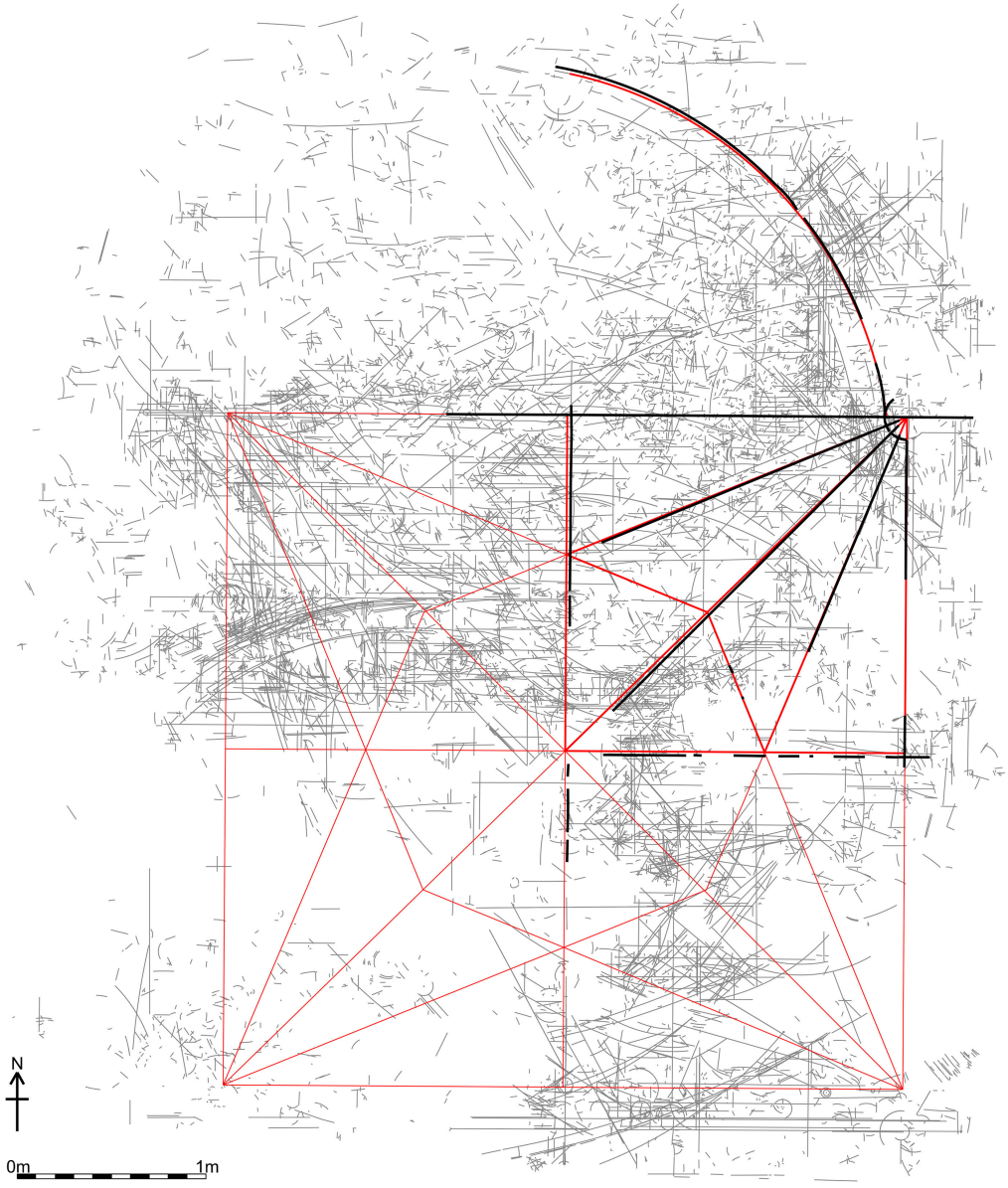


Figure 6
Digitally retraced lines and arcs of the tracing floor (grey) with east cloister inscribed lines highlighted (black). Hypothesised 2D bay design and 3D arc overlaid (red).

ometry of the vaulted ceilings, the methodology of which we have previously described in detail (Webb and Buchanan 2017).

## RETRACING THE TRACING FLOOR

In comparing the three survey methods, photogrammetry and the resulting orthomosaics in particular provided the clearest and most comprehensive record of the tracing floor. To begin this manual retracing process, orthomosaics were first imported as TIF files into MicroStation V8i. The orthomosaics exported from Metashape were at a high resolution due to the necessity to include as much detail in the image as possible, resulting in large file sizes that could slow down the tracing process in MicroStation. Therefore, these orthomosaics were tiled on export and arranged in the correct location on import into MicroStation using georeferencing.

The drawing was set up by first producing a 0.5m grid over the orthomosaics to enable a methodical and detailed tracing of grid tiles individually, the same way that a site grid is used on archaeological sites. Traced lines were added as a separate layer, as well as the centres of arcs. Each tile was searched in turn, starting at the south west corner and proceeding left to right and row by row. When a straight line was found, it was traced using the 'Place Line' command. When a true arc was found, it was traced over using the 'Place Arc' command, set to 'Start, Mid, End'. Where curves were found not to be straight or a true arc, the 'B-spline by Points' command was used. Using a combination of these commands, sometimes based on trial and error, we were able to fully retrace the floor (figure 6).

Although we were able to trace more lines than those previously found in analogue surveys, the data was still problematic, in part due to varying image quality from the photogrammetric survey. Some curves were clear, sharp inscriptions on the surface, but these could be partially obscured by lower image quality or lighting. Other curves appeared as a less-clear surface abrasion of some kind, perhaps smoothed down over time to leave a duller surface. Other marks include light 'scars' on the surface, perhaps caused by age or water damage. Additionally, the plaster floor includes cracks that have appeared over time, which can sometimes be confused with inscribed markings if they are straight or arced in nature. The opposite issue also occurred, where lines or arcs appeared to have broken open to form a crack, perhaps the result of moisture damage. Therefore, judgement calls had to be made of whether to redraw in these cases or not. Our next phase of digital tracing will review these curves to account for levels of certainty in the data.

Next, to test the effectiveness of RTI, we traced over one target area (0.3 x 0.2m once the reflective spheres and scale bar were cropped out) and com-

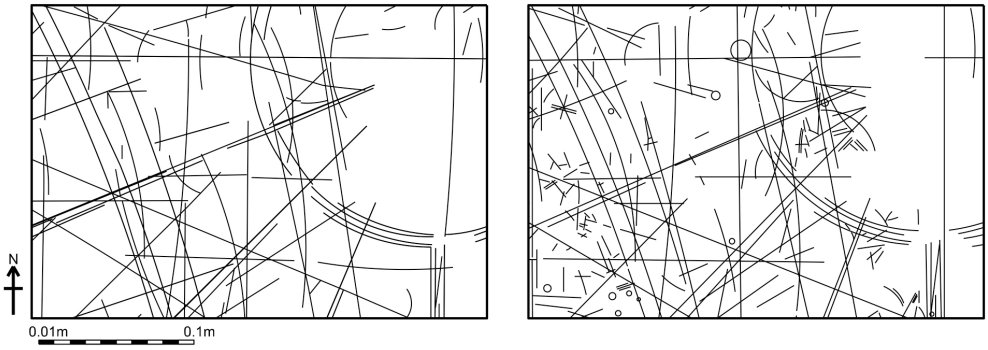


Figure 7
Sample area comparing tracing over the photogrammetry generated orthomosaic (left) and RTI export (right).

pared it with that already traced using photogrammetry. The RTI tracing process was similar to that of the photogrammetry orthomosaics: a jpeg image of the RTI model set to 'specular enhancement' was imported into MicroStation, a grid was overlaid and each square systematically traced over. The main difference was having to toggle between MicroStation and RTI Viewer to change settings and move the simulated light source. Comparing this with the photogrammetry generated equivalent revealed that more detail was found (figure 7), however, this may have been as the tracer was working on a smaller area, compared to the photogrammetry generated version which covered the entire tracing floor. Nevertheless, the sample area does suggest that more detail can be found using the RTI process, and it will be useful when attempting to pinpoint specific geometry, such as an arc centre point that cannot be found using the photogrammetry generated orthomosaic. In this example, we could then use the RTI method to scrutinise specific areas in greater detail.

## COMPARING THE TRACING FLOOR TO THE EAST CLOISTER WALK

The last attempt to analyse the tracing floor was made by Pacey as part of an extended study of medieval architectural drawing (Pacey 2007). This research was conducted using the existing drawings and photographs of Harvey, comparing them with new tracings of selected parts of the floor. Pacey identified two groups of lines with specific architectural features at Wells. The first was a window from the east walk of the cathedral cloister; the second, a half plan of the vault above it. Whilst Pacey did attempt to confirm this using analogue measurements, he also suggested that testing his hypothesis would require more precise surveys of the floor and cloister. Our research attempted to answer this call through the use of digital surveying techniques.

### *Analysing the 2D plan*

Laser scanning of the cloister was conducted with a 1/4 resolution and 4x quality, giving a scan time of approximately 15 minutes per bay. The results were processed using Faro's proprietary software, producing detailed mesh models of its vaults. A run of three bays was selected from the east walk of the cloister, which we have designated E6 to E8 (figure 2). The models of these bays were then exported into Rhinoceros 6, where the intrados lines of their ribs were retraced using the 'Section' command. Using the 'top' view, the lines of the longitudinal and transverse ribs were extended with the 'Polyline' command and their points of intersection forming the corners of the plan were located on a horizontal plane, enabling measurements of each bay.

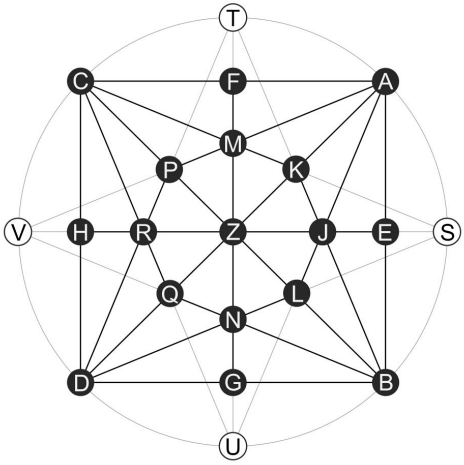


Figure 8
2D Hypothesis

Whilst the plans of these vaults (figure 8) are usually identified as square, in reality they are slightly rectangular, with an average width of 3.631m across their transverse sides (AC, BD) and 3.549m across their longitudinal sides (AB, CD). These were compared with the dimensions recorded from the digitally retraced tracing floor (figure 6). Though the half plan laid out on the floor is fragmentary and many of its lines are intermittent, the dimensions of the upper quadrant can still be reconstructed in some detail. The resulting quarter plan measures 1.779m on the north side at the base of the window tracery and 1.799m on

the east, which presumably corresponds to the transverse side of the vault. These dimensions would give lengths of 3.558m for the window side and 3.598m for the transverse side, providing close matches for those recorded in the actual vault. This indicates that the disparity in dimensions in the cloister's plan, being slightly rectangular rather than true squares, was not just an accidental product of the construction process, but a deliberate choice which had been taken into account during the planning process.

With the plan of the vaults measured, it is possible to develop and test hypotheses for how it was laid out by masons. Our assumption has been that it was produced at a 1:1 scale in 2D, either on a dedicated tracing floor or some other available flat surface. Analysis of the cloister bays at Wells has revealed that the 2D geometry of their plan could potentially have been laid out using the 'starcut' method, a geometrical proportioning device as named by Stewart (2009) and further investigated by us, notably as a 'circle starcut' variation (Buchanan and Webb 2017). The rectangular plan of the bays is laid out, measuring 3.558 x 3.598m. Diagonals are drawn from corner to corner (AD, BC), then a circle is drawn centred on the middle of the bay (Z), with a radius extending to corners A, B, C, D. Further lines are drawn through the midpoints of each of the bay's sides, quartering the vault and its enclosing circle through E, H and F, G. The intersections between these lines and the outer circle (S, T, U, V) are then connected to bay corners forming chevrons (AUC, AVB, CSD, DTB,) creating the 'circle starcut'. This geometrical figure allows the vault to be divided into any theoretical set of proportions based on the dimensions defined by the outer circle. Tiercerons AJ, AM, BJ, BN, CM, CR, DN, DR are added using this starcut geometry, and finally the central octagon JLNQRPMK is added by connecting their crossing points. This hypothesised 2D geometry was then superimposed on the plans of the vaults themselves, showing a close match between theoretical model and reality.

Yet whilst this model can reproduce the lines of the actual vaults, this does not necessarily mean that it was the exact method used by the medieval masons. Unlike our other sites, the tracing floor at Wells gives us an unparalleled opportunity to test our methods directly against medieval design practices. Overlaying our theoretical model on the tracing floor produces a close match between model and reality (figure 6), but the results raise more questions than answers. Construction lines which we would expect to find are not present, and of the starcut there is no trace. This is strange because there is ample evidence that several aspects of the vault's design were still being worked out at full scale. Alternative angles are visible for several of the ribs, numerous test lines were drawn for the transverse side of the bay and a series of concentric circles can be found revealing the potential springing points.

### *Analysing the 3D design*

Once the 2D geometry of the vault had been laid out, its 3D geometry was explored. The ribs were digitally traced from our 3D mesh model of the cloister and their curvatures quantified using best fit arcs following the lines of the trace. By measuring the radius, apex height and centres of these arcs, it is possible to identify the geometrical methods which could have been used to create them. For the cloister's east walk, it was discovered that all of the ribs were laid out using a fixed radius. Its recorded values range from 2.075-2.357m, with an average of 2.149m and a standard deviation of 0.064m. The method for applying this radius to each of the ribs was relatively straightforward. The rib's maximum height and length on the plan are defined, allowing its springing point and apex to be identified (figure 9, blue crosses). A circle of the fixed radius is drawn centering on both the springing point and the apex (figure 9, green circles), their point of intersection providing the centre for the rib (figure 9, red cross). An arc of the fixed radius is then drawn from this centre, passing through both the apex and springing point (figure 9, red circle).

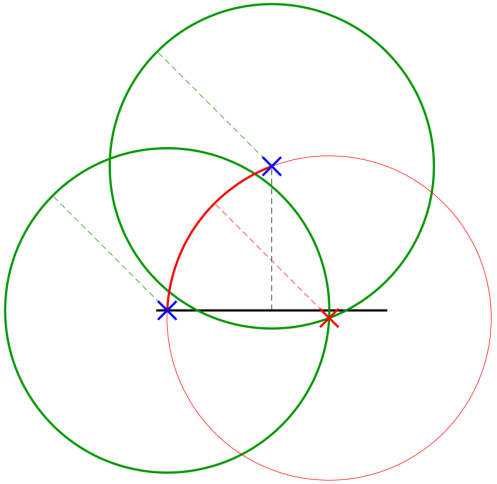

Figure 9
'Three circles' method of calculating the missing arc centre.

The only rib shown on the tracing floor is the wall rib relating to the window (figure 6). Whilst there is no sign of any construction lines relating to the method described above, the radius of this arc is exactly 2.151m. This is an exceptionally close match for the average in the cloister's east walk and it is therefore plausible that the radius for the vault's ribs was derived from the design of the window. This could be some indication of why none of the other ribs were laid out on the tracing floor. Once the radius had been established there was no further need, as the same curvature could be applied to all of the stones being cut for the vault ribs.

## REFLECTIONS AND CONCLUSIONS

Testing different survey methods showed that photogrammetry is the best technique in the situation described. As 3D digital models derived from photogrammetry and laser scanning proved unhelpful, we will test structured-light 3D scanning, such as an Artec Leo, at future sites. RTI will continue to be used, particularly where a high level of detail is present, to allow greater forensic investigation. Virtual RTI, in which an existing 3D model is rendered with the light source changed to multiple positions around a target area, will also be explored. We will also investigate the use of pattern recognition and machine learning as potential methods of automating the tracing process, both for the 2D floor and 3D vault ribs.

At Wells, we will continue to study the geometry of the tracing floor to look for further matches beyond that suggested in the east cloister, as we have the entire east end of the main cathedral digitally surveyed. Our first investigation will focus on the ogee arches that can be found in the corners of the tracing floor survey, as well as the window tracery. We also hope to extend our surveying of floors to the Chapter House at Wells cathedral, and other sites such as York Minster and Bourges cathedral.

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# How to Explore the Architectural Qualities of Interactive Architecture

## *Virtual or physical or both?*

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*While the theoretical possibilities and implications of interactive architecture are promising, much still is unknown how these can be practically translated towards purposeful deployments. To understand the true dynamic qualities of interactive architecture, the only method is experiencing its hedonic qualities firsthand. To this end, working prototypes need to be realised and their actual impact measured. In this paper, we compare two potential experimental strategies for interactive architecture prototype evaluation, as we benchmark the conceptual, technological and methodological differences between a life-size, physical prototype and an immersive virtual reality simulation. By presenting the preliminary findings of each strategy, we discuss how their unique strengths and weaknesses could complement each other in future research endeavours.*

**Keywords:** *interactive architecture, physical prototyping, virtual reality prototyping, human-building interaction*

The concept of interactive architecture is often perceived as a technological solution for a problem that is still rather unknown (Costa Maia et al. 2015), mainly because its practical conceptualisation within more realistic contexts is challenging. Put differently, although the possibilities and implications of interactive architecture are promising at least in theory (Achten 2015, Oosterhuis 2012), we still do not know how these can be utilised towards reaching useful purposes that actually matter. Meanwhile, recent alignment of architecture, neuroscience and psychology has shown evidence of how architecture can influence people's states of mind, such as sense of well-being, aesthetic judgments and hedonic experience of pleasure (Techau et al. 2016, Vartanian 2015, Vartanian 2013). To this end, there exists numerous causal factors in interactive architecture, none the least in terms of physical manifestation and in interactive features, that could potentially influence its effectiveness. Due to the unpredictable dependencies between all these factors, it is evident that their combined effects can only be revealed by way of real, empirical experimentation that allows humans firsthand experience. After all, the experience of space

depends on the interplay of a rich variety of aspects, ranging from atmospheric qualities to material characteristics and more. To avoid costly investments in and unsatisfactory implementations of interactive architecture, more practical evaluation methods and generalisable expertise need to be established that reveal the most crucial dimensions of interactive architecture alongside their potential application domains. By combining the emerging interests of scientific disciplines like human-computer interaction (Alavi et al. 2019, Lundgaard et al. 2019) with those of architectural research (Achten 2013, Fox and Kemp 2009, Oosterhuis et al. 2007) we propose several new methodologies to take on this research challenge.

## CONTEXT OF THE RESEARCH WORK

### *Interactive architecture*

Architecture, including all its defining components (Brand 1994), has always been subject to change. Its inhabitants change, together with their individual desires and needs. Even within families or fixed cohorts of inhabitants, spatial preferences change throughout the years, months, seasons, days, hours, or even on a much more immediate basis. The functions that architecture typically hosts tend to change numerous times throughout its lifetime, as they are dictated by various contextual and societal dynamics that are difficult to predict. Yet despite these dynamic constant tension between the varying functions and the static form they are hosted in, architecture is rarely conceived as an adaptable or flexible entity.

Enabled by networking, sensing, and processing technologies, there are now few restrictions of what can be digitally captured, stored, analysed and reasoned upon about what happens in the physical world. Driven by more recent technological developments in robotics and domotics, the field of interactive architecture now stands in front of an era in which physical reality can be (pro-)actively manipulated and enacted upon. The field of Human-Computer Interaction (HCI), situated at the crossroads of social sciences and computing, has shown particular interest in providing scientific methods for designing, prototyping and evaluating ways how such interactivity could reach more purposeful goals. Emerging subdisciplines like Human-Building Interaction (HBI) and Interactive Surfaces and Spaces (ISS) are now rapidly exploring the possibilities of embedding computing technologies within the built environment (Wiberg 2015). Research in Evidence-Based Design (EBD), which focuses on augmenting design decisions with significantly valid empirical forms of evidence, is providing the first real proof how ergonomic design of architecture can benefit people's health and satisfaction (Ulrich et al. 2008). For instance, it has been shown that the careful orchestration of spatial qualities such as lighting, sounds, textures, colours, layouts are able to evoke particular human experiential effects to occur through a multimodal and multisensory process (Barrett et al. 2013, Elsen et al. 2014). With the help of the HBI, ISS and EBD disciplines, we thus believe that interactive architecture could advance from achieving highly compelling hedonic spatial experiences towards more measurable and purposeful goals.

### *State of the art*

The close integration of interactive technology in the built-environment requires a deeper understanding of people's behaviour in space. By framing the subjective architectural experience in more objectively measurable factors, various studies have hinted towards more sophisticated proxemic measures to help understand complex space-use behaviours, such as a person's location (Alavi et al., Verma et al. 2017), field of view (Fender et al. 2017), or spatiotemporal comfort preferences (Alavi et al. 2017).

Technology-driven studies demonstrated the feasibility of provoking social interactions between people and architectural components on different levels of scale, ranging from moving furniture to transforming building-sized structures. For example, previous experimental studies have shown the social and spatial effects of a sofa with personality traits (Spadafora et al. 2016), a mobile chair that

persuades people to sit (Agnihotri et al. 2016), a shape-changing bench in public space (Grönvall et al. 2014), or a vibro-tactile wall (Morrison et al. 2016). Some studies discovered how dynamic architecture is able to affect people's thoughts and emotional states, such as by synchronising the movement of an immersive structure to people's respiration (Jäger et al. 2019, Schnädelbach et al. 2016), choreographed body postures (Schnädelbach et al. 2018), the occupant's location in space (Kilian 2018) or physical presence through a facial detection system (Shi et al. 2019). Others attempted to integrate interactivity in existing spatial fabric, such as by implementing a window-wall that changes its transparency adaptively to the environment and inhabitant's preference towards comfort and sustainability (Bader et al. 2019), or an ergonomic curtain that evolves and adapts alongside inhabitants based on their daily behaviours and preferential input (Bak et al. 2016). Accordingly, next to reaching obvious functional and human comfort goals, interactive architecture seems apt to be exploited as a form of expression that affect people's experience in equally holistic, multimodal and multi-sensory ways than its prototypical 'static' counterpart (Zhao et al. 2017, Iyendo et al. 2016).

Literature also demonstrates that some experiential qualities of interactive architecture can be measured to some extent, through firsthand experiments in either a controlled (i.e. Schnädelbach et al. 2016) or in-the-wild environment (i.e. Agnihotri et al. 2016). Such studies are articulated by the combination of qualitative and quantitative methods, such as digital data logging and polling of participants' preferences (Alavi et al., Verma et al. 2017), narrative walks through Wizard-of-Oz method, in which the interactions are controlled by hidden human operators (Spadafora et al. 2016), semi-structured interviews and post-think-aloud sessions for participants to relive, recount or interpret their lived experiences (Bader et al. 2019), observations of physical behaviours and/or social interactions (Grönvall et al. 2014), and physiological measurements to reveal hidden reactions such as eye gazing, skin conductivity or heart rate sensing (Jäger et al. 2019).

### *Motivation*

According to Pallasmaa (2005), "Architectural space is lived space rather than physical space, and lived space always transcends geometry and measurability." The experiential impact of architecture is beyond functional and measurable values, but exists through the interplay of many hedonic aspects, ranging from atmospheric qualities to material characteristics and more. To study these architectural experiences, especially in the case of interactive architecture in which time is a crucial factor, 'real-world' experimentation seems required. Practical solutions exist in prototyping and testing mixed-fidelity testbeds, that allow us to observe, capture, analyse and benchmark human experiences.

In this paper, we discuss the implications of two experimental strategies that aim to reveal the effects of relatively simple forms of interactive architecture on humans by way of 1) the firsthand experience of a realistic simulation, and 2) empirically observing and surveying that experience. We propose that the simulation can be manifested via an immersive, life-sized prototype in either virtual or in physical reality. While a physical prototype provides conditions that come close to the real-scale architecture, recent studies in VR now show how virtual simulations have become a viable alternative solution to some extent (Hermund 2018).

In our first implementation, the virtual strategy simulated a museum space that contained a collection of moving panels carrying a collection of artworks. Occupants were able to freely navigate within the virtual world while the panels responded to their locations by moving away or towards them. Afterwards, feedback was obtained and the interaction logs analysed. In the physical strategy, a folding panel involving two connected wings moved dynamically in an attempt to augment a certain simulated scenario of space use. The actual impact was enacted and evaluated during two 'bodystormed' experiments: the first one to explore its rich design

space, and the second one to reveal the resulting experiential qualities. By benchmarking the conceptual, technological and methodological differences between both experimental strategies alongside their impact on the results, we will overview their respective strengths and weaknesses, and will discuss how they could be deployed in future investigations of interactive architecture.

The two studies in this paper, therefore, follow a design-oriented research methodology (Fallman 2007), which goals consist of revealing new knowledge how people experience interactive architecture, rather than the prototypes themselves, nor their design process.

### *Apparatus*

The work reported in this paper is the result of a collaboration between two architectural research groups from different universities in Europe. The Research[x]Design group at KU Leuven has experience on human-computer interaction research, such as in-the-wild studies of new technological applications in public settings. The Department of Architectural Modelling at CTU in Prague has profound expertise on the theory of interactive architecture. Through a combined research project under the CELSA programme of KU Leuven, called 'Purposefully Controlling Mediated Architecture', the two groups joined forces to further their complementary understanding of interactive architecture, and to develop new means to investigate this phenomenon.

We present the main findings of two finished Master degree diploma projects, which were accomplished at the university of KU Leuven. At its Faculty of Engineering Sciences, a master thesis project typically requires an effort of 24ECTS spread over two semesters. Students can choose to develop an architectural design, or a 'hybrid' form of research, i.e. combining both a designerly as well as a scientific form of academic investigation. As next to prototypical architectural design courses, their main degree consists of various obligatory engineering courses such as introductory programming, electricity, energy, and domotics. Some students feel motivated and empowered to investigate more technologically-driven endeavours that require a certain degree of custom hardware (e.g. electronics) or software (e.g. VR) development. Those students select a master thesis theme that necessitates the custom development of a novel technological application, and are expected to also thoroughly and critically evaluate its actual performance in real world settings.

During our collaboration, we aimed to move away from a purely technological exploration 'for it's own sake' towards conceptualising more meaningful applications of interactive architecture. We are fully aware that this could raise the bar to a possibly unreachable goal, since so much is still unknown in terms of the true effects of making architecture 'responsive'. Next to sharpening the theoretical underpinnings of interactive architecture in terms of what it can actually achieve, we thus focused on exploring research methodologies that are able to objectively assess its potential effects on human experience. Foremost, we believe that experiencing a prototype on architectural scale firsthand allow occupants to move from imagining a spatial experience to actually experiencing a more holistic confrontation of the interplay of many potentially valid architectural qualities with all their human senses. Through such a direct confrontation, we may observe aspects of architectural interaction that cannot be predicted, let alone imagined.

## VIRTUAL PROTOTYPE EXPERIMENTATION STRATEGY

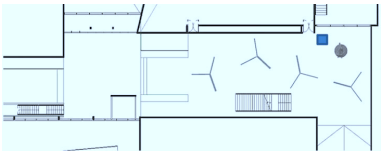

Figure 1
Ground plan of the museum M entrance, the experimental space, with the dynamic panels.

The overall context of the virtual experimentation strategy was situated in M-Museum Leuven. To provoke curiosity and interest, we designed a set

of moving panels to together form an exhibition space. Using virtual reality (VR) technology, this semi-controlled study investigated how people experience interactive architecture by controlling all architectural dimensions except of two (i.e. movement and proxemics), and critically reflected upon the applicability of VR towards this goal.

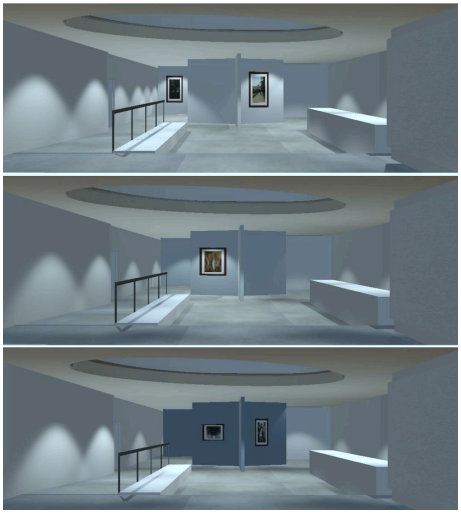

Figure 2
The three scenarios in the experiment, each featuring a different dynamic state of the panels' movement, from top to bottom: Fixed, Rotation and Translation. The colour of the panels indicates the movement amplitude. The darker colours imply that the panels will move more dramatically.

## *Methodology*

**Design rationale.** The research began with an iterative design process, during which the panels' spatial orchestration and interactivity were prototyped, tested and modified throughout three pilot studies with participants. Throughout this preliminary phase, the student noted how participants did not relate sounds with recognising spatial changes, and they had difficulty recognising more subtle types of panel movements. As a result, we exaggerated the panel movements in terms of intensity, and simplified their animation complexity. Lastly, it was noted that material aspects like shape, size and colour influenced how panel movements were perceived, and how they were considered to be architecturally integrated within the overall space.

**Experiment design.** The prototype consisted of four panel formations, each made of three separate wings, held together on one edge and spreading approximately 120 degrees apart. The overall orchestration of formations created an overall exhibition walkthrough connecting several intermediate spaces (Figure 1). Each panel wing hosted a painting or photograph, which as a collection was changed among the different conditions to maintain the interests of the participants throughout the whole within-subject experiment. Three different scenarios were implemented and compared, each featuring a different dynamic state: 1) the formations were static and fixed (Fixed); 2) the formation rotation center remained fixed, yet each wing was able to rotate away or towards the participant (Rotation); and 3) the formations were able to move towards or away from the participants (Translation) (Figure 2).

**Procedure.** The experiment, taking approximately one hour per participant, took place in a university lab room, which was equipped with a HTC Vive VR set. After the initial interview about personal background (e.g. gender, age, profession) and prior VR experience, each participant was asked to fulfil a practice session to get acquainted with all the necessary VR functionalities. Each participant experienced all three scenarios in a random order, during which navigations and visual fields were recorded. Each scenario was followed with a questionnaire to gather the experience, which was developed based on two vocabularies that capture architectural qualities (Ching 2007) and interactivity (Lenz et al. 2013). The questionnaire was deliberately situated within the VR environment itself, enabling the participant to fill in her answers while still experiencing (instead of remembering) the space itself (Schwind et al. 2019). In addition, a standard user experience questionnaire (UEQ) was conducted after the two interactive scenarios. Finally, a semi-structured interview was taken to gather more qualitative insights from the participants.

### *Main findings*

**Movements and scenarios.** Most participants preferred the Rotation scenario, which can be explained by at least two reasons: 1) the smoothly rotating motions contributed to the exhibition purpose by gradually showing the artworks; while 2) creating spatial effects that were described as "more challenging" to make sense of. The Translation scenario was experienced as more straightforward, understandable, simple and uniform. Some participants mentioned that movements that pointed towards them were considered 'scary'. We noted that participants spent more time in the Translation scenario, primarily since the widening and narrowing of pathways caused by the linear movements made it harder to navigate. The content of the artworks had influence some on the experience, as paintings and photos with colour drew more attention, and the scenario with famous paintings (in Rotation) was often considered favourable.

**VR as a research tool.** The simulated virtual environment presented several practical limits, such as the unnatural type of navigation and the unrealistic quality of the rendering and shadowing effects, making the walls seem to float at places. Yet it also showed great promise to quickly and efficiently test multiple and different conditions while maintaining a fully controlled, and thus identical, study context. Participants themselves believed that the space looked sufficiently realistic to render representative responses. While the study also implemented a novel method to integrate a questionnaire inside a VR environment itself, none of the participants reported difficulties using it.

Since most of the participants had little experience with navigating in a VR environment, some of the results might be biased - even when we included a practice session at the start and randomised the order of the scenarios. For instance, some participants kept struggling with moving through the small spaces without bumping against the walls, even in the Fixed scenario, yet we noticed significant improvements as the experiment progressed and participants became accustomed to the navigational features.

## PHYSICAL PROTOTYPE EXPERIMENTATION STRATEGY

A set of wall-like panels was developed, which could be moved via a custom control software. The architectural and interactive qualities of these panels were evaluated during two qualitative experiments, in order to: 1) establish an understanding of the possible behaviours that the panels could convey, and 2) evaluate the impact of these behaviours to actual human occupants of the space.

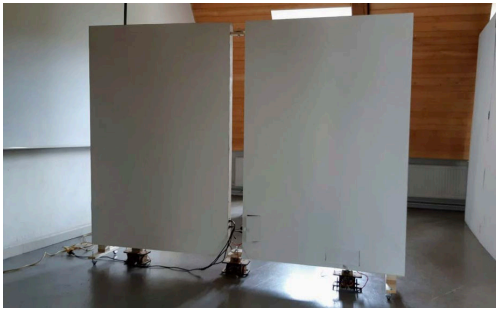

Figure 3
The dynamic panels with two interlocked panels carried by three wheeled robots. The panels can fold to create a semi-enclosure.

### *Methodology*

**Design and prototyping.** Considerable time and effort of the research was dedicated to the design and fabrication of the interactive architecture prototype itself. The panels had to be: able to execute moderately complex movements; controlled with a simple user interface; disassembled to be transported; and sufficiently large to provoke real architectural qualities. The panels consisted of a foldable wooden frame, constructed from two connected panels (120 x 200cm) and weighting 9kg each. White cardboard plates formed the outer finishing material, being stiff and aesthetically neutral (Figure 3). Three separate double-wheeled robots were installed at each hinge point, which were collectively controlled through an Arduino electronics board that listened via a Bluetooth connection to the instructions of a laptop com-

puter that was located closeby. Whereas the addition of batteries would render the whole installation wireless, the effort required to overcome its technical complexity was considered too severe.

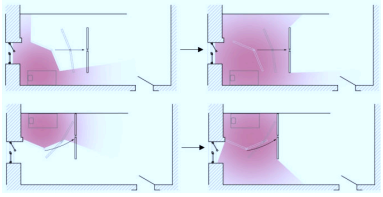

Figure 4
Scenario S1 (top) and S2 (bottom) for sleeping activity, in which the panels try to transform a 'closed, dark' space into a 'open, bright' space.

**Design space exploration.** The first experiment consisted of a hands-on design session with participants in order to identify the spatial qualities that could be created, and how they could be used to achieve particular architectural purposes. The participants are architectural practitioners and students recruited by the researcher. By interactively controlling the actual panels located within a university room, the participants were requested to determine the location and movement of the panels to facilitate two scenarios: reading and sleeping. Afterwards, the panels were controlled to perform the resulting motion patterns for the participants to experience their design first hand.

The main findings of the experiment revealed at least three architectural qualities that the prototype was able to actuate. It was able to manipulate: 1) the overall lighting by linearly moving towards the light source; 2) the openness of the space by moving in an 'open and close' pattern, hereby affecting the visual privacy and spatial layout; and 3) the overall atmosphere by using a subtle yet repetitive, and thus calming, motion pattern. These qualities are not exhaustive and mainly transpired by reasoning around two predefined human activity scenarios of sleeping and reading, which are both 'quiet' and 'relaxing' in nature. Overall, we did not notice significant differences of the interactive features between the two scenarios, except that they aimed for the opposite goals. For instance, while reading required light to illuminate a text, sleeping demanded the absence of light.

**User study.** Six distinct scenarios were conducted in the Wizard-of-Oz method, in order to capture the effect on three activities: sleeping, reading and being creative. During the experiment, the participants and the researcher deliberately communicate in a narrative walk approach (Spadafora et al. 2016). Specifically, the sleeping activity included two scenarios during which the panels either try to allow (scenario 1, i.e. S1) or block (S2) the light source coming from the window (see Figure 4). The reading activity tested the aspects of subtle shaking motion in peripheral vision (S3); and visual openness with the panels move around the participant, blocking and opening their visual field repetitively (S4) (see Figure 5).

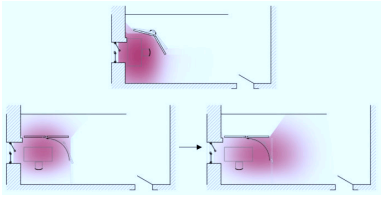

Figure 5
Scenario S3 (top) and S4 (bottom) for reading activity, with subtle motion in peripheral vision (S3) and changing visual openness (S4).

During the creative activity, the participants were able to choose between drawing or playing music, and the previously mentioned affordances were combined into two scenarios. In scenario S5, the panels performed a shaking motion towards and away from the participant, aiming to create a 'calming' atmosphere. In scenario S6, the panels moved towards the participant in an obtrusive gesture, dramatically changing the spatial layout and visual openness (see Figure 6).

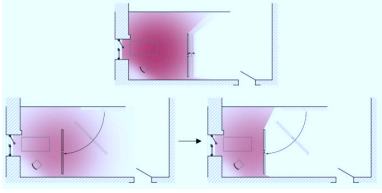

Figure 6
Scenario S5 (top) and S6 (bottom) for creative activity, aiming to create 'calming' or obstrusive' atmosphere.

The six scenarios were deployed in a university room and shown to eight participants while they 'bodystormed' and performed the actual human activities

as realistically as possible, each taking approximately 75 minutes in total. After each scenario, the participant was given a quasi-identical questionnaire that polled for both spatial and interactive qualities, after which a semi-structured interview was conducted.

### *Main findings*

**Spatial experience.** In contrast to the seemingly more conclusive results of the first experiment, the results of the second experiment were more diverging. While there were no conclusively common experiences for each scenario, some clues emerged that could explain why the reactions of participants differed. First, there was a tendency to resist how the environment changed, in that some participants found it difficult to get used to the notion of a wall that moved. Secondly, while the participants were asked to focus on their given activity (e.g. sleeping, reading), this also refrained them from noticing any movement until when they were confronted by a dramatically changed situation. Lastly, we noticed how personal preferences could generate opposite results. For example, while one participant did not enjoy scenario S2 because she felt isolated, another participant preferred this scenario for the exact same reason.

**Novel affordances.** Despite some diverging results, several unique spatial and interactive qualities were achieved. For instance, the experience of waking up in a bigger and brighter space than the one they commenced sleeping in was rated 'pleasant' by most participants, and the repetitive motion was also confirmed to have calming and soothing effects. Some unforeseen spatial qualities were reported, such as the dynamic reflections of the panels on the surrounding walls. Unfortunately, these affordances were dependent on environmental conditions and thus became not always visible to the participants, because of their relative position, activity and personal preference.

**Position-oriented movements and motion-oriented movements.** Two types of interactive behaviour could be distinguished. Position-oriented movements influence spatial qualities by gradually changing the spatial layout. For example, a wall can move extremely slowly so that its movement cannot be detected, and the outcome is only recognisable after several hours (e.g. which could be useful for a sleeping scenario). In contrast, motion-oriented movements influence spatial qualities through the nature of the motion itself. For example, a repetitively subtle motion can only achieve a calming effect when its movement is observed more consciously. This study thus suggests that interactive architecture should take into account not only different static states, but also 'how' these states change and animate from one to another.

## OBSERVATIONS

Conceptually, virtual prototypes can provide 'idealized' conditions, where realistic aspects like actuator (robot) noise, lag in response speed, and so on, can be eliminated. Material parameters such as colour, texture and even movement are relatively easy to change. The context (e.g. changing to another architectural space) and environment (e.g. weather, light) can also be quickly modified. However, virtual prototypes are immaterial, 'removed' from an occupant's direct and haptic experience. It can only address a limited set of sensory, with a different balance of prominence from reality, which may affect the reliability of the study results. Meanwhile, physical prototypes have the advantage that they can influence the very wide spectrum of an occupant's perception. This makes it possible to identify and gauge unexpected side-effects that occur through the interrelatedness of senses, and the immediacy of the physical prototype to the bodily experience. Difficult to simulate clues like light, shade, smell, and sound are automatically included in a physical prototype, making it relatively valid in terms of ecology. At the same time, the interplay of spatial qualities of this holistic experience make it difficult to isolate and investigate affecting factors.

In terms of methodology, virtual prototypes have the advantage of operating an integrated sys-

Table 1
Comparison of physical prototypes and virtual prototypes experimentation strategies.

| Comparison factors | | | Virtual Prototype | Physical Prototype |
|---|---|---|---|---|
| **Conceptual** | *Experience* | Architectural experience | Immaterial | Embodied |
| | | Architectural qualities | Individual variables control | Holistic interplay |
| | *Condition* | Scenario | Idealized circumstances<br>Fully controlled | Unforeseen circumstances<br>Relatively ecologically valid |
| **Methodological** | *Learning curve* | Technical familiarity | Learn VR features | Readily accessible |
| | *Experiment* | Available strategy | Benchmark comparative values<br>i.e. time, place, heatmap | Bodystorm real-world activity<br>and social interaction |
| | | Quantifiable data measures | Available in VR set | Require hardware set up |
| | | Qualitative data collection | During the experience | After the experience |
| **Technical** | *Skills* | Design and prototyping | Standard software & hardware<br>Approachable | Customized software & hardware<br>Require several skills at once |
| | *Experiment* | Technical control | Set-up beforehand | Control in real time |
| | *Effort* | Main time consumption | Study design | Hardware design and prototype |
| | | Main financial investment | VR equipment | Materials |

tem that provides various automatic tracking functionalities. This makes that multiple experimental conditions can be benchmarked easily by extraction and exaggeration of comparative variables, such as activity and interaction logs of both time (e.g. durations) and space (e.g. locations). The VR interface also allows qualitative questionnaires to be integrated during the experiment, i.e. inside the virtual environment. However, since not everyone knows how to use VR initially, there is exist a potentially influencing learning curve, one that for some people (e.g. depending on age, computational literacy) might be quite steep. Because VR experiments always take place 'behind' a screen or a set of goggles, the user will always start out in an isolated condition. This very act of 'stepping inside a different world' biases the experiment, and makes it more removed from reality. Physical prototypes, on the other hand, do not require participants to have any technical familiarity, supporting real-world activities which they can really enact, play or do - although some suspension of disbelieve exists here as well. This allows further research strategies to become potential useful, such as bodystorming, in-the-wild studies involving unknowing passers-by, or tracking the movements and interactions of multiple people occupying the same space. Yet, applying such methodologies in the physical world wold require sophisticated hardware infrastructures, including sensors or camera tracking, which in and by themselves might influence the human experience too significantly.

Technically, virtual prototyping has the advantage that 'any' interactive system can be modelled regardless of its complexity. Most VR sets come with standard software and hardware, which can be learned quickly and debugged easily, allowing more time for the experiment design and set up. Since they do not require physical construction, the financial investment is relatively low. Meanwhile, building a physical interactive system demands knowledge of multiple skills at once, including but not limited to (computationally) designing, programming, prototyping and fabricating the whole setup. While the technical and material resources needed for physical prototyping are also not always economical or easy to obtain, the software is also not standardised, which creates a lot of time consumption in the preparation phase. The whole process of physical experimentation, therefore, is more labour intensive and less tolerant of mistakes comparing to virtual experimentation. An empirical comparison of two experimentation strategies is shown in Table 1, based on three aspects: conceptual, methodological and technical differences.

Overall, the most profound experience of interactive architecture can be reached through the real

built environment (Figure 7). However, given the large investment related to creating a space on an architectural scale, the creative possibilities for architectural experimentation and its scientific evaluation is relatively limited. To this end, both virtual and physical experimentation facilitate the wide and varied probing of different kinds of experiences with interactive architecture. What should not be forgotten, however, is that these experimentation strategies cannot substitute an 'interaction narrative' that involves a concrete daily life. This is a role for the real built environment and our conscious taking part in the real world - not as consumers, but as architects and designers.

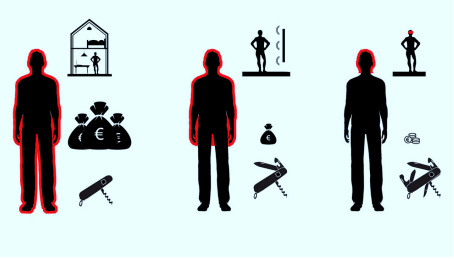

Figure 7
Relationship between building, physical prototype, and virtual prototype and their levels of investment, engagement, and flexibility.

## CONCLUSIONS

In this study, we demonstrated the applicability of two experimental strategies, i.e. virtual and physical prototypes, for the goal of studying interactive architecture. We presented and discussed in depth two practical evaluation studies. We analyzed their respective advantages and pointed out their differences which affected the research in terms of conception, methodology and technicality. Overall, while virtual prototypes allows for a more flexible research set up and requires less effort in preparation, physical prototypes provide more ecologically valid conditions and readily open up for further research strategies such as in-the-wild study and social interaction. Therefore, we propose that virtual prototypes offer a viable alternative at the early research phases, when exploring the design space of interactive possibilities. Meanwhile, first-hand experience of participants with physical prototypes could be more suited at later phases, such as to obtain empirical evidence of the embodied, holistic architectural experience. As a result, the combination of both strategies allows researchers to work more efficiently in terms of the deployment of research methods and realisation of the interactive architecture, while ensuring that all evidence is being gathered in relatively ecologically valid contexts. However, we suspect that the combination of both strategies requires a certain consistency throughout the research, especially in maintaining the behaviours and aesthetics of the virtual prototype and its physical version, in order to obtain reliable results.

We realise the relative limited complexity of the presented studies, particularly as they also transpired from master thesis work that required a lot of effort in terms of mastering the required technical skills as well as the required research methodologies. If the entry level of students would already encompass these skills, then much more progress could have been made and more profound experiments may be realized. This means however, that the discussion what interactive architecture is and the associated skill-set must be integrated in the architectural education.

Finally, through the quick probing and testing of virtual and physical prototypes, it is possible to quickly cover a wide terrain of possible interaction scenarios and techniques - in a much broader fashion than is possible through realized buildings. Thus the role of virtual and physical prototyping is not just one of clear scientific and academic interest to understand the phenomenon of interactive architecture, but it can also play an important role to eliminate and root out dead ends of certain design ideas and their implementations that would result in costly yet ineffective applications in real buildings. It has to be repeated however, that only through the combined knowledge and experience on all levels - buildings, physical, and virtual prototypes, within a developing theoretical framework - we can gain the best understanding of interactive architecture.

## ACKNOWLEDGEMENTS

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# The Bio-inspired Design of a Self-propelling Robot Driven by Changes in Humidity

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*Plants use highly reliable nastic movement through the oriented hygroscopic swelling of tissue to autonomously respond to external stimuli. Buildings, on the other hand, use highly unreliable kinematic mechanisms with multiple failure-prone components that are dependent on electromechanical input. Literature describing stimulus-responsive shape-changing actuators focuses primarily on single-stage reversible movements, and therefore provides limited insights into the methodologies needed to achieve directed multistage locomotion. Here we describe a methodology to develop a self-propelling and programmable robot (Hygrobot) capable of flexible locomotion with the cyclic introduction and removal of moisture. Several multi-layer mechanisms were programmed to actuate sequentially with changes in moisture, in a choreographed manner, to generate locomotion. We expect that this approach can advance interest into hygroscopic self-propelled mechanisms, as well as foster further research into the development of more complex kinematic mechanisms, requiring articulated and multi-stage actuation, for direct architectural or robotic implementation.*

**Keywords:** *Bio-inspired, shape-changing, programmable materials, robotic locomotion*

## INTRODUCTION

Wood is a hygroscopic material. With a change in moisture content, it shrinks and swells anisotropically, affecting strength, stiffness, and fracture morphology (Dinwoodie, 2000). Commonly regarded as a deficiency (Simpson, 1983), nature has found multiple avenues to augment and expand the dimensional change of cellulose tissue as a highly efficient actuation mechanism. Unlike plant movements actively driven by turgor variations and osmotic gradient, which require the plant to be alive and require metabolic energy, passive swelling and shrinking of tissue can occur long after the plant is dead - even in semi-fossilized structures (Poppinga et al., 2018; Poppinga, 2015). In other words, the direction and magnitude of actuation is programmed in the structure of the tissue itself and therefore operates autonomously in response to external signals like humidity. Passive swelling drives the movement of wheat awns, the self-burial of seeds, the shrinkage of some types of mosses, and the opening and closing of pinecone scales (Reyssat and Mahadevan,

2009). Pinecone scales are a key bio-mimetic model for bilayer material structures that curl in response to moisture. They open when the air is dry and close when the air is wet, a reversible and repeatable process vital for fertilization (Figure 1B-1C). This shape-change is passive, and is considered to be 'biologically programmed' within the tissue (Dawson et al., 1997).

Stress-induced bending in bilayers was established by Timoshenko in his work with bi-metal thermostats (Timoshenko, 1925). This functional bilayer principle has been widely referenced in the literature regarding stimulus responsive shape-changing mechanisms. This includes hygroscopic wood mechanisms (Reichert et al., 2015, Ruggeberg and Burgert, 2015, Holstov et al., 2015), 4D printed mecha-

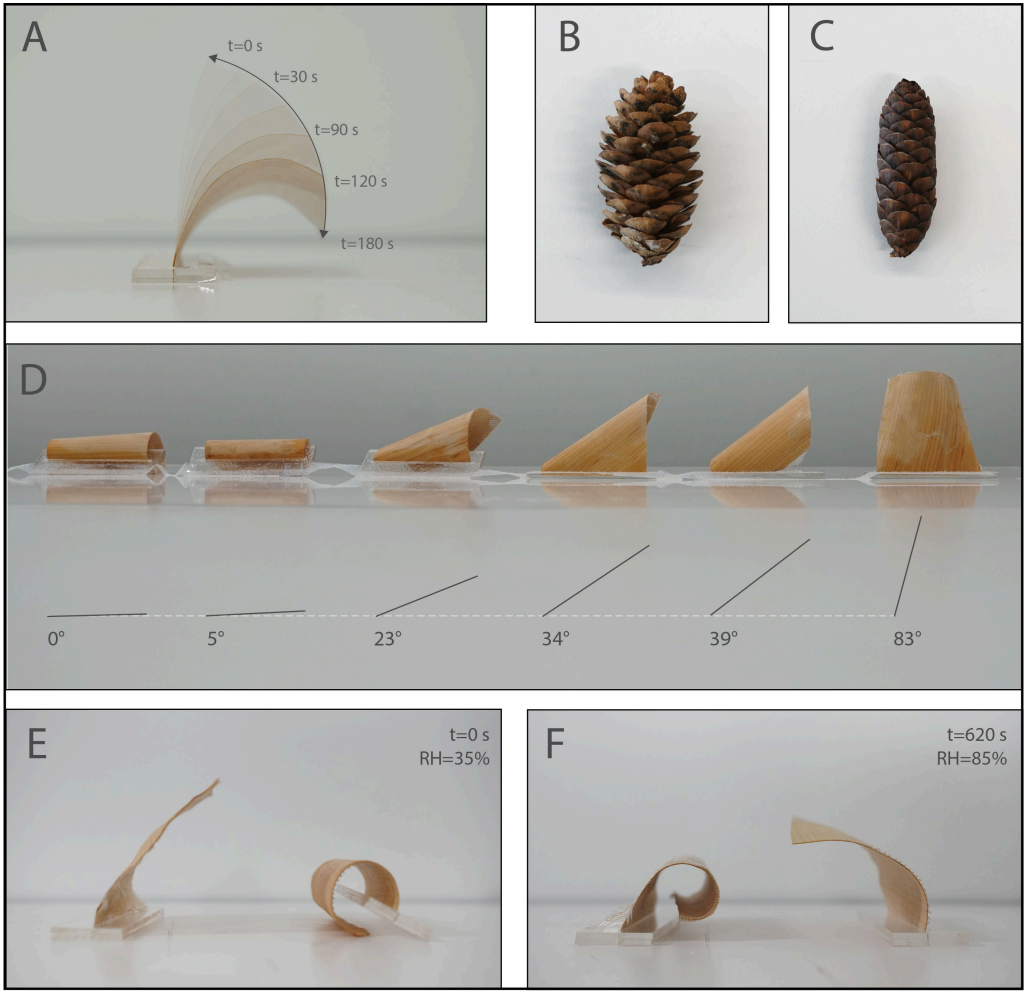


Figure 1
A: Hygroscopic bend initiated by changing relative humidity in air over time in a wood veneer and fiberglass bilayer. B-C: Hygroscopic bend initiated by increasing relative humidity in air over time in a pinecone scale (t=0 and RH=10%, to t=25 min and RH=85%). D: Differences in bend angle depending on grain direction after moisture introduction (t=180 s, RH=85%). E-F: Differences in bend direction depending on moisture level of active layer at fabrication (left sample in both E, F fabricated at RH=35% and right sample in both E, F fabricated at RH=85%).

nisms (Tibbits, 2014, Wood et al., 2016, Gladman et al., 2016, Han et al., 2018), thermo-responsive metal bilayers (Sung, 2016), and hybrid wood-metal composites (Abdelmohsen et al., 2019). Samples are generally developed to achieve continuous curvature but localized bending has also been proposed by limiting the bilayer region relative to the sample, to form hinge like mechanisms (Tibbits, 2014).

Wood is a naturally grown material with a highly oriented structure that is highly differentiated based on the wood grain orientation (Gibson and Ashby, 1997). Hygroscopic expansion is highly variable between wood species or even within different specimens of the same tree due to natural variation (Dinwoodie, 2000). Moisture-responsive shape-changing bilayers have been fabricated by bonding quarter sawn maple with an inactive layer of glass fiber textile (Reichert et al., 2015, Holstov et al., 2015, Abdelmohsen et al., 2019), or by cross laminating maple or beech with spruce veneer (low hygroscopic swelling) to create an all-wood bilayer (Wood et al., 2016, Ruggeberg and Burgert, 2015, Dierichs, 2017). Testing of glues and optimized fabrication parameters for wood bilayers has provided valuable insight into the large-scale implications that this system may offer (Vailati et al., 2017, Vailati et al., 2018). Beyond wood lamination, there has also been ongoing research into the potential of 3D printing in the development of wood polymer composite bilayers, using wood or cellulose fibers embedded in polymer inks (Gladman et al., 2016, Erb et al., 2013, Correa et al., 2015).

In architecture, Michelle Addington (2005) states that "Smart Materials are essentially material systems with embedded technological functions". These functions, and specifically the computational capacity of materials, have fascinated engineers, physicists, and architects (Addington, 2005; Harding, Miller, and Rietman, 2008; Toffoli and Margolus, 1991). Using this "material intelligence" (Kwinter, 2001), in conjunction with the cyclical changes in humidity and temperature, these hygroscopic actuation mechanisms can have a key role in reducing energy consumption and carbon emissions in the built environment (Poppinga et al., 2018). Applications of hygroscpopic wood actuators in architecture include building skins (Reichert et al., 2015), larger scale shading mechanisms (Vailati et al., 2017), and a solar tracking device for photovoltaic applications (Ruggeberg and Burgert, 2015). However, all of these existing actuators are fixed in place, and at the moment there is limited literature that investigates their potential as untethered systems capable of moving independently. Research by Dierichs and Wood has addressed the potential of granular climate responsive components capable of re-configurable self-assembly (Dierichs, 2017), but no known research exists that has particularly looked at locomotion as the key performance driver for hygroscopic mechanisms. The presented paper accordingly outlines a proof of concept that demonstrates a primitive four-legged robot (Hygrobot) programmed to self-propel with a change in humidity. We demonstrate and quantify the potential for a localized bilayer region to limit the angle of curvature and produce a joint-like bending effect for multistage locomotion.

## MATERIALS AND METHODS

### *System Variables*

The stimulus-responsive behaviour of a hygroscopic bilayer system is affected by a series of parameters. These parameters can be controlled to calibrate when, and how, a bend will occur.

**Active Layer Type and Thickness.** Quarter-sawn maple veneer with 0.8 mm thickness was used as the active layer. Maple was selected given its lower modulus of elasticity, grain direction homogeneity, and decay resistance (Reichert et al., 2015). A quarter-sawn veneer cut was selected due to greater consistency in grain and radial expansion (Dinwoodie, 2000). Consistency in the grain direction is important as this directionality is directly correlated to the direction of swelling. Changing the angle of grain orientation in the sample correlates to a change in the direction of bending (Figure 1D).

The actuation response time is directly affected by the rate of moisture diffusion throughout the component. Therefore, larger thickness in the active layer requires more time to reach equilibrium, holding off natural deformation for longer (Reichert et al., 2015). The time required for the bilayer to shape-change is determined by the speed of change in the relative humidity and the rate of moisture intake by the sample.

**Inactive Layer Type.** The restrictive layer constrains the expansion of wood. Based on the referenced literature and preliminary testing, either an epoxy and fiberglass layer (Figure 1), or a strictly epoxy layer was used throughout this work.

**Relative Humidity.** Moisture is the primary driver of movement in hygroscopic bilayers, and specifically relative humidity (RH). RH represents the ratio of the vapour pressure of the air to the saturated vapour pressure of the air (Dinwoodie, 2000). For a given vapour pressure and air temperature, there is an equilibrium moisture content for wood where no vapour will travel in or out. As the vapour pressure or temperature changes, so too does the moisture content of the wood, attempting to reach equilibrium (Dinwoodie, 2000). When wood is bonded to an inactive layer, environmentally sealed on one side, a stress gradient occurs between the two layers, resulting in the bending of the bilayer. As such, we can define the behaviour of a hygroscopic bilayer bend in terms of the relative humidity of its surrounding air.

RH can also be defined as a function of the absolute moisture content in the air and the air temperature. Warm air can hold more water than cold air, meaning for a given amount of moisture in the air, as temperature increases, the % RH will decrease. Accordingly, % RH can be changed by adjusting the absolute moisture content in the air while leaving the temperature, or by adjusting the temperature while leaving the absolute moisture content (Dinwoodie, 2000). Because of the above relationship, changes in temperature can have a direct effect on % RH. As such, experiments were conducted in a sealed environmental chamber, or a room with a consistent air temperature (approx. 23° C). To change humidity, a series of ultrasonic humidifiers were used throughout the research.

**Moisture Content of Active Layer at Bond.** The shape of the wood layer and moisture content at the time of lamination corresponds with its rest condition. A bilayer laminated at low moisture will bend upon moisture intake. Oppositely, a bilayer laminated at high moisture will bend during moisture desorption. Any bilayer can be programmed to bend at a specific humidity, depending on the moisture content of the wood at the time of lamination. Figure 1E-F shows a bilayer laminated at low moisture content and a bilayer laminated at high moisture content first in low RH and then in high RH. The addition of moisture into the air can be seen to have the opposite shape-change effect on each bilayer.

### *Preliminary Experiments*

Grain orientation and moisture content of the active layer at bond were tested individually. For both experiments active samples (maple veneer) were laser cut to the same square shape, 10 cm x 10 cm in size. In the first experiment, samples were cut at a different angle relative to the grain, ranging from 0° to 83°. The samples were prepared in a low RH environment using a drying oven for 30 minutes at 100° C, and lamination and curing was conducted in low RH (approx. 10% RH at 23° C). The samples were exposed to a change from 35% RH to 85% RH, while the temperature was kept constant at 23° C (Figure 1D). In the second experiment, samples were bonded at either low (approx. 10% RH at 23° C) or high RH (approx. 70% RH at 23° C), and the effect of moisture introduction and removal was observed (Figure 1E-F).

### *Hinge Experiments*

To study the effect of hinge location on bilayer sample bending, eight veneer samples were fabricated measuring 5 cm x 15 cm each. Samples were prepared in a low RH environment (approx. 10% RH at 23° C). Samples were fabricated with controlled local bilayer regions (as opposed to the full length of

the sample). Each region was created by pressing the maple veneer layer against a stamp of a controlled size, sealing the veneer samples within the region of contact only. The size of the contact region remained consistent throughout this experiment (15 mm x 5 cm), and the location was varied experimentall (Figure 3B-C). To study the effect of hinge size on bilayer sample bending, eight bilayer samples were fabricated in the same manner as above. In each case, the stamp thickness varied in size. The location of the contact region centre remained consistent, about 4 cm from the fastening axis (Figure 3D-E).

### *Hygrobot Fabrication*

The Hygrobot uses four actuated legs attached to an inactive acrylic body. Each leg measures 8 cm long and 1.75 cm wide. The legs were prepared using the epoxy stamping methods described above, and stamps were applied halfway up each leg to create localized bending, mimicking the effect of a knee joint. The feet of the legs were given claws to increase friction during movement. The 0.75 mm thick acrylic body was hollowed out to reduce weight. The legs were attached to the body using fishing cord and two-part epoxy resin. Figure 4 (right) shows the Hygrobot at rest.

## RESULTS

### *Preliminary Experiments*

Individual tests were performed to demonstrate both the relationship between grain direction and moisture content of the active layer at bond to shape-change. This preliminary experimentation is consistent with previous literature (Reichert et al., 2015), demonstrating that the angle (Figure 1D) and direction (Figure 1E-F) of a bilayer bend can be controlled through the calibration of the material preparation and the fabrication process.

### *Computational Model*

A geometric model was designed to approximate the curvature observed in physical samples when exposed to humidity (Figure 2). A linear relationship was then established between sample curvature and humidity and was used in this model to accurately predict bend severity between 35%-85% RH. The sample curvature change in bending was defined along a single arc, and was thus simplified to account only for uniaxial bending caused by the expansion or contraction of cellulose tissue in the active wood veneer component of the bilayer.

### *Location of Hinge*

The relationship between the location of a targeted bilayer and the overall bend of a sample was tested. The bilayer location was changed relative to the fastening axis across eight samples, varying in distance (14 mm intervals), beginning at 3.5 mm from the axis (Figure 3B-3C). Equation 1 in Figure 3 shows the linear relationship between the seal location centre, x, in mm from the fastening axis, and percent aperture opening, f(x), as viewed from the normal to the bilayer surface at C. The percent aperture opening is calculated by dividing the temporary aperture area (created with the bilayer bend) by the overall bilayer area at rest.

### *Size of Hinge*

A subsequent experiment was conducted to test the relationship between the size of a targeted seal and the overall bend of a bilayer. The length of the local

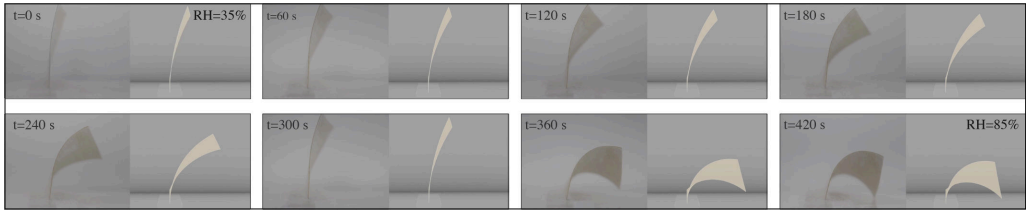


Figure 2
Physical model (left) against computational model (right) with a change in humidity and time

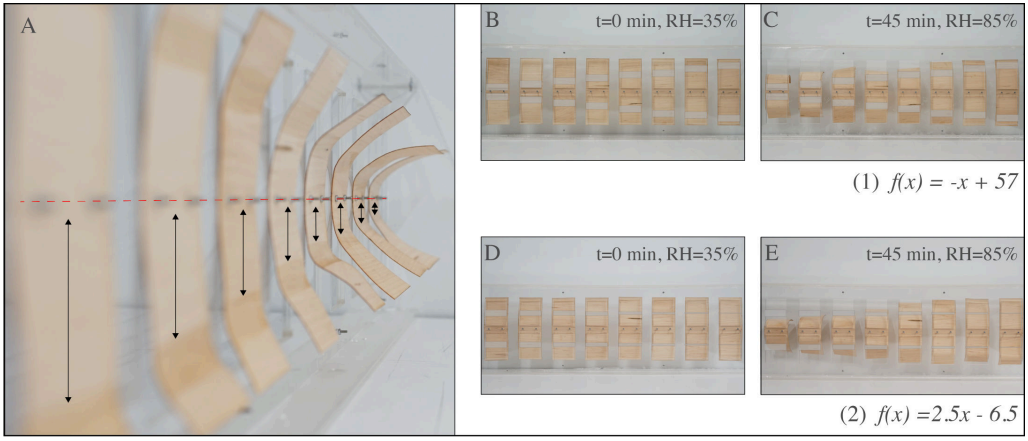


Figure 3
A: The effect in the variation of targeted stamping location with moisture introduction on bend degree. Samples at t=45 min, RH=85%. B-C: The effect in the variation of targeted stamping location with moisture introduction on bend degree. The grey rectangles represent the location of the stamp, and targeted bend axis. D-E: The effect in the variation of targeted stamping size with moisture introduction on bend degree. The grey rectangles represent the location of the stamp, and targeted bend axis.

targeted bilayer increased from 1 mm to 15 mm, increasing by intervals of 2 mm (Figure 3D-3E). Equation 2 in Figure 3 shows the linear relationship between the length of the seal, x, in mm, and the percent aperture opening, f(x), as viewed from the normal to the bilayer surface at E. The percent aperture opening is calculated in the same manner as described above.

These tests demonstrate that a lamination methodology can be effectively used to control the degree of a bilayer bend. From this, we can program bilayer samples to achieve specific bending curvature in a reversible and repeatable manner.

### *Four Stage Movement of Hygrobot*

Based on the presented control mechanisms, we developed a robot (Hygrobot) that could achieve independent locomotion, self-support, and self-propelled displacement across a given surface over time based on relative humidity changes in the environment. In nature, several biological organisms use friction to propel, or to amplify, their applied movement. For example, snakes rely on surface roughness to initiate their movement, and many other animals rely on obstacle or surface friction to climb or dig (Denny, 1980). Similarly, seeds use cellulose-based nastic motors to dig themselves into the ground (Burgert and Fratzl, 2009). Existing literature presents various examples of abstract models that attempt to translate similar animal movement robotically (Shepherd et al., 2011). In our case, the movement of Hygrobot is based on a repeating set of four moves. Figure 4 displays each of these moves in order, illustrating cyclic motion.

The first step targets movement in the front legs, actuated through the local depositing of moisture via spray in an otherwise low-humidity environment. These legs were programmed to bend with high moisture (approx. 85% RH locally), such that when moisture is deposited, bending occurs at the bilayer joint. The moisture-induced bend causes the "locking" of the front legs to the ground, at which point, unable to overcome static friction, pull the back legs and body towards them (Figure 5A).

The second step targets movement in the back legs. Like the front legs, the back legs were programmed to bend with high moisture (approx. 85% RH locally), such that when moisture is deposited, bending occurs at the bilayer joint. The moisture-induced bend brings the back legs up towards the front legs (Figure 5B).

The third move involves further movement in the back legs. The back legs, which are currently bent, are actively dried using heat from a drier to flatten,

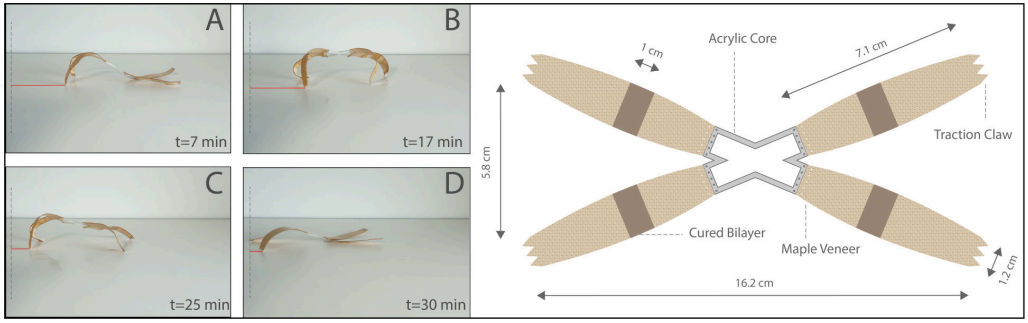


Figure 4
Left: Four step cyclic movement of the robot with targeted humidity introduction and time. Right: Plan diagram of Hygrobot at rest (approx. 35% RH).

coming back to equilibrium moisture. This flattening motion pushes the robot forward, unlocking the front legs from the ground (Figure 5C).

In the fourth move the front legs return to equilibrium, flattening as they dry, and leaving the robot back in its rest state in a new position (Figure 5D).

The four-step cycle was repeated four times over the course of 127 minutes. Each cycle lasted roughly 30 minutes and the robot moved a total of 43 cm. The temperature and humidity in the room remained constant throughout the experiment (T=24° C, RH=35%) as moisture was introduced only locally to the legs. Figure 6 displays the progression of the Hygrobot over time.

## DISCUSSION

We have fabricated a hygroscopic robot that can move with targeted moisture introduction and removal. This device is actuated using a four-step cycle, generated by locally depositing and removing moisture to the front and back legs in a coordinated sequence.

### *Limitations*

The low thickness of the system's legs gives an adequately fast response to moisture changes in the air, but also proves to be a structural liability over time. Over-saturation can cause plastic deformation of the wood, rendering it non-elastic, and less responsive to humidity. Uneven moisture introduction across the grain can also cause microstructural damage in the material, further reducing its responsiveness to humidity (Reichert et al., 2015). In almost all the sample experiments, noticeable differences in the responsiveness of the legs over time (> four cycles) were observed, and we speculate that the oversaturation from our experimental process was the cause. The time-scale for movement presents further challenges. The average speed of the Hygrobot through an entire cycle of movement is around 2.5 mm/min, far slower than many mechanized robotic systems.

### *Future Research*

Hygrobot relies on targeted moisture introduction for locomotion. It is speculated that by programming the front and back legs to bend and dry at different moisture, a natural humidity cycle could drive locomotion entirely. For example, its back legs could be programmed to bend at a higher humidity than the front legs such that, with an increase in humidity to a fixed point, only the front legs would bend and, with a further increase in humidity to a second fixed point, the back legs would bend. Theoretically, if non-localized moisture cycles could be effectively demonstrated as drivers of movement, robots could be calibrated to move according to the outdoor, or indoor, humidity cycles in various locations, permitting predictable and repetitive moisture patterns.

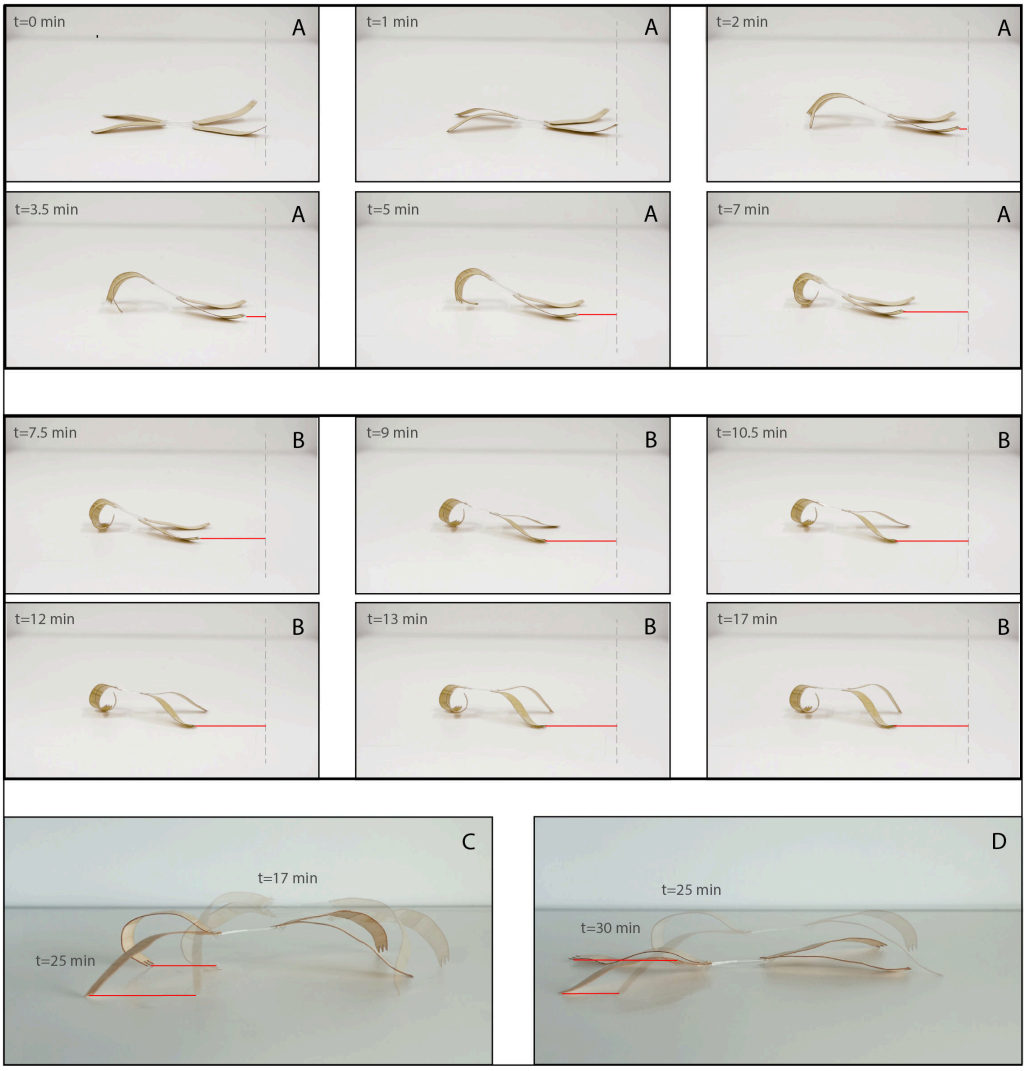


Figure 5
Locomotion of Hygrobot. A: The first move, with targeted movement of the front legs (left side of body). B: The second move, with targeted movement of the back legs (right side of body). C: The third move, with targeted movement of the back legs (right side of body). D: The fourth move, with passive drying releasing the body back to rest.

While moisture-induced movement due to daily fluctuations in arid regions would likely be dramatic but slow, tropical regions might allow for more rapid humidity fluctuations that could occur within a matter of hours. Future applications for locomotion remain speculative, but the ability to move through a landscape in search of specific environmental criteria, much like plant's seeds do, could provide valuable

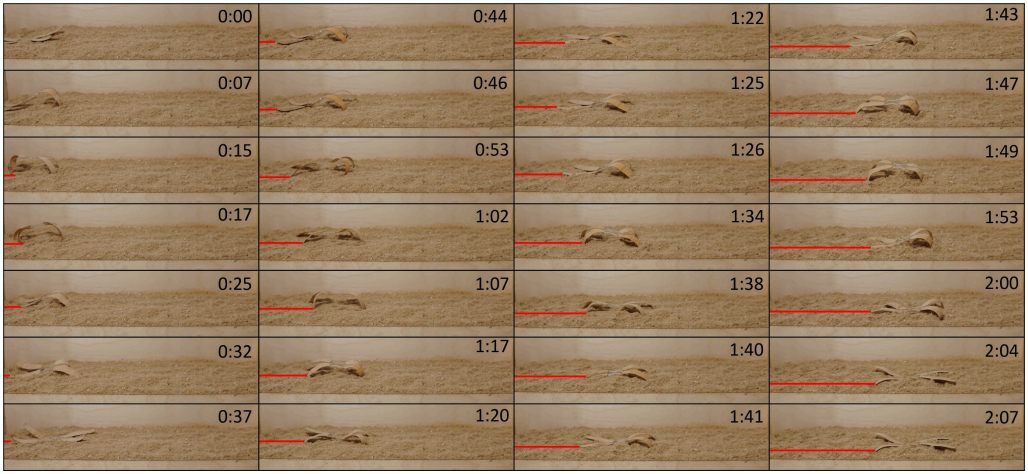


Figure 6
Hyrgobot progression over time (in hours and minutes). Final red progress bar (2:07) is 43 cm in length.

opportunities for terraforming. Furthermore, moisture induced changes in geometry could provide potential applications to reduce soil erosion and prevent landslides.

A variation in the curing process between right and left legs or in the angle of fastening relative to the grain could allow for turning capabilities, and thus multi-axis movement. Terrain conditions and feet geometry could also be further investigated.

Finally, there exists potential in expanding self-propelling robotic movement beyond hygroscopic systems. Similar mechanisms could be devised using temperature (thermal expansion in metal bilayers), or a combination of both active and passive systems as drivers and controllers of movement.

## CONCLUSION

In this paper, we demonstrate a hygroscopically activated robot, capable of self-propelled locomotion and self-support with targeted moisture introduction and removal. Future studies should further investigate locomotion in direct relation to naturally occurring humidity cycles and with multi-directional flexibility.


## *Acknowledgements*

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# HelioPhilia Intelligent Kinetic Canopy

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*In the contemporary changing world, digital architecture is to bring us new horizons and opportunities to take a determining step toward future. It results in speed and precision in process of design and construction. Moreover, the world is shifting to smartness. This paper is to develop a comprehensive mechanism to design an innovative canopy inspired from nature. Therefore, the canopy is going to inspire from young sunflowers. The canopy consists of a multi-functional waffle-frame. The main wing of the platform structure can have alternative utilization and the amount of light passing through it can be adjusted by using shade on the waffle spaces. Solar panels can also be used on the frames conductive to supply the energy independently. This HelioPhilia canopy always seeking the daylight, therefore, it cast a shadow behind itself to provide much more comfortable environment for whom choose there to be inside as a user. The results emphasize on the role of learning from nature in successful digital design process.*

**Keywords:** *HelioPhilia Architecture, Intelligent Architecture, Kinetic Spaces, Digital Fabrication, High-Performance Architecture, Interactive Design*

## INTRODUCTION

This research emanates from a project in the HAL (High-performance Architecture Lab) located at Tarbiat Modares University (TMU) defined as "Interactive Transforming Canopy with Particular Reference to Computational Design Thinking". The canopy should provide a comfort zone with novel technologies, understanding that, the canopy itself should show high level of interactivity (Figure 1). As a result, the design team were challenged to examine their ideas and innovations through designing the canopy. The main issue of this experience was the coherence and harmony between theoretical ideas and design to performance process. The team decided to design a canopy which be kinetic and also intelligent to sync itself in a way to meet the users' needs by Using digital technologies. Kinetic architecture allows occupants to experience new environments which could cause raising the efficiency (Mansourimajoumerd, et al. 2018). The team believed that all we need is available in nature and people just need to investigate more to extract a mechanism which is sufficient and sustainable. Therefore, it was crucial for the team to design a mechanism which has inspired from the nature. Through the systematic deconstruction and codification of the rules, or logics, that regulate various material/construction systems, it is possible to close the gap between the representation and the artifact (Al-Haddad et al. 2010).

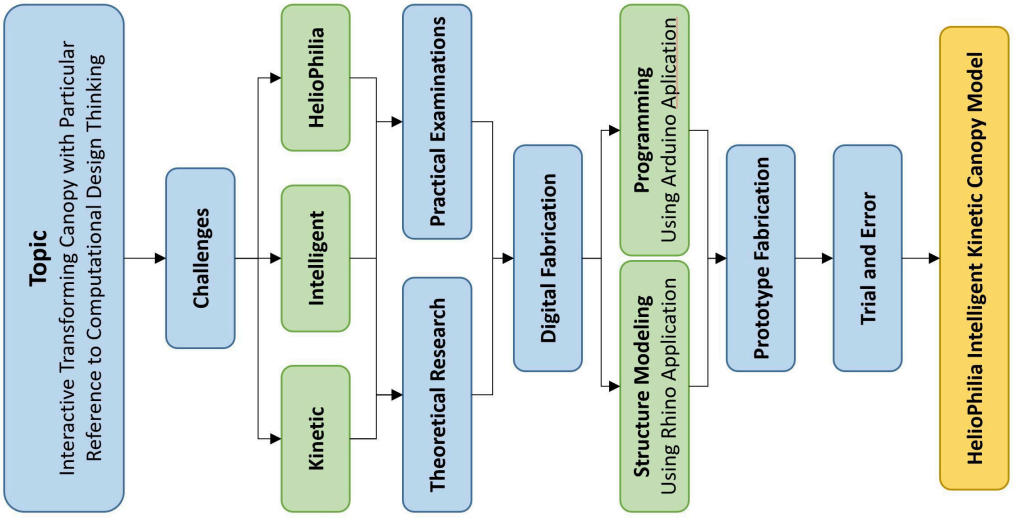



Figure 1
Research Method
[Authors]

## INSPIRING CANOPY

### *Elytra filament pavilion*

The Elytra Filament Pavilion celebrates a truly integrative approach to design and engineering (Figure 2). As a centerpiece of the V&A's Engineering Season it demonstrates how architectural design can unfold from a synergy of structural engineering, environmental engineering and production engineering, resulting in unique spatial and aesthetic qualities. Instead of being merely a static display, the pavilion constitutes a dynamic space and an evolving structure. The cellular canopy grows from an onsite fabrication nucleus, and it does so in response to patterns of in habitation of the garden over time, driven by real time sensing data. The pavilion's capacity to be locally produced, to expand and to contract over time provides a vision of future inner city green areas with responsive semi-outdoor spaces that enable a broader spectrum of public activities, and thus extend the use of the scarce resource of public urban ground. While allowing for a glimpse of the future, the pavilion also draws inspiration from a striking architecture of the past: The Victorian Greenhouses. They embody the profound impact that the first industrial revolution had on architecture and showcase the experimental spirit of architects and engineers that embrace the adoption of new modes of making and materials in a truly explorative manner. In a similar way, the installation seeks to forecast how the so-called fourth industrial revolution of robotics and cyber-physical production systems enables the emergence of new structural and material systems.

A second design inspiration is the unsurpassed effectiveness and resourcefulness of living nature. Today, with the help of advanced computational design, simulation and fabrication we can tap the vast reservoir of biology and explore the underlying working principles of natural systems in design and engineering. The pavilion is the outcome of four years of research on the integration of architecture, engineering and bio-mimetic principles. It explores how biological fiber systems can be transferred to architecture. The 200 $m^2$ pavilion structure is inspired by lightweight construction principles found in nature - the fibrous structures of the forewing shells of flying beetles known as Elytra. [1]

Figure 2
Elytra Filament Pavilion [1]

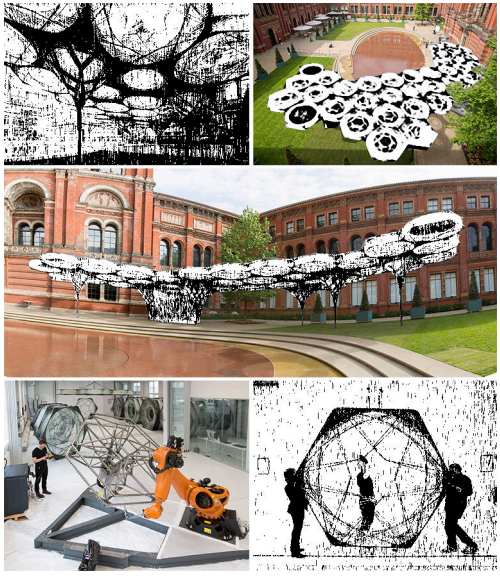
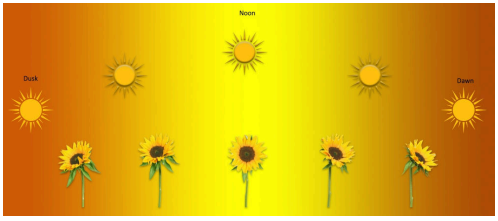


Figure 3
Concept Diagram [Authors]

The fibrous composite structure of the installation only consists of two basic cells, the canopy cells and the column cells that interface between the inhabitable ground and the canopy, which is also equipped with transparent roof panels. Both cells are made from the same load-bearing fiber material: transparent glass fibers and black carbon fibers. The production itself is an innovative robotic winding process developed by the project team, which in contrast to most other composite fabrication processes does not require any mold, and thus reduces waste to a minimum. Here the raw materials - simple, small and lightweight spools of fiber that are pre-impregnated with resin - are used for the onsite production of composite building elements that form additional cells of the canopy structure.As there is no predetermined final state, the canopy is equipped with fiber optical sensors that allow for the real time sensing of the forces within the structure. This allows monitoring the changes to the structural systems caused by the further growth and adaptation of the canopy, which is driven by anonymous data on how visitors use the canopy space captured by thermal imaging sensors and interpreted in conjunction with the measurement of environmental parameters such as temperature, radiation, ambient humidity and wind. The real-time sensing combined with the onsite fabrication renders the canopy a learning system and evolving structure that will grow and reconfigure over the time of the exhibition, based on the behavior of the garden's visitors, and their preferred places to walk, stroll, rest or meet. The canopy constitutes a fibrous tectonic system that is as architecturally expressive as it is structurally efficient. It provides the visitor with a unique spatial experience that transforms and evolves over time. [1]




## DESIGN CONCEPT

The main challenge that the team has specified is designing a system which get inspired from a mechanism of the nature. In order to opt the utmost conformable concept to the subject of the project, sunflower (binomial name: Helianthus annuus) have been chosen among many other possibilities. Young sunflowers orient themselves in the direction of the sun. At dawn the head of the flower faces east and moves west throughout the day (Figure 3). When sunflowers reach full maturity they no longer follow the sun, and continuously face east. Young flowers reorient overnight to face east in anticipation of the morning. Their heliotropic motion is a circadian rhythm, synchronized by the sun, which continues if the sun disappears on cloudy days or if plants are moved to constant light (Atamian et al. 2016). This idea provides canopy with being kinetic by changing the orientation and being intelligent by detecting the sun light, recognizing it, and following it.

Daylight and views provide a strong connection to place and time, and they promote healthy circadian rhythms, reduce stress, and improve productivity, attentiveness, and mood (Mahdavinejad et al. 2017).

"HelioPhilia" (Helios is sun in greek, and Philia, means friendship or love) is inspired as the main concept. Designed team has considered this word in consequence of light loving characteristic of the canopy. Being faced directly to the sun light is what the canopy does and it define the canopy as a Helio-Philic construction. Therefore, Users can take advantage of a permanent shadow and comfort inside the interior space.

## PROTOTYPE FABRICATION

### *Structure*

Structure was modeled with Rhinoceros software. The structure consists of a waffle frame and a column which is bearing the load (Figure 4). The waffle frame provides us with some panel-like spaces that can be used for solar panels, pattern frames, or shades for controlling the amount of passing light thorough the canopy. Each piece of the prototype had been precisely cut by laser cut machine. Then we weave and connect the pieces together (Figure 5). The material that is used for the prototype is MDF 3mm. Two Servo-motors are used to perform the vertical and horizontal movement (Figure 6).

### *Programming*

In order to have the ability by which the canopy could be able to adjust itself to the light direction, we programed a code using Arduino application. Then, we installed four photocell sensors on the waffle structure which is able to carry the information of light amount to the main processor (Arduino Uno kit). The range of movement in vertical and horizontal orientation can also be adjusted through the code. In this scale, a flashlight is used as the main light source to play the sun role for the canopy. First, sensors collect the information of how much light each of them is gaining and send them to the core. Second, the processor calculates the average of bottom and top sensors. Third, it calculates the average of left and right sensors. After comparing them, decides to move in the direction of having the major amount. The following pseudocode illustrates the original code which is written in appendix section.

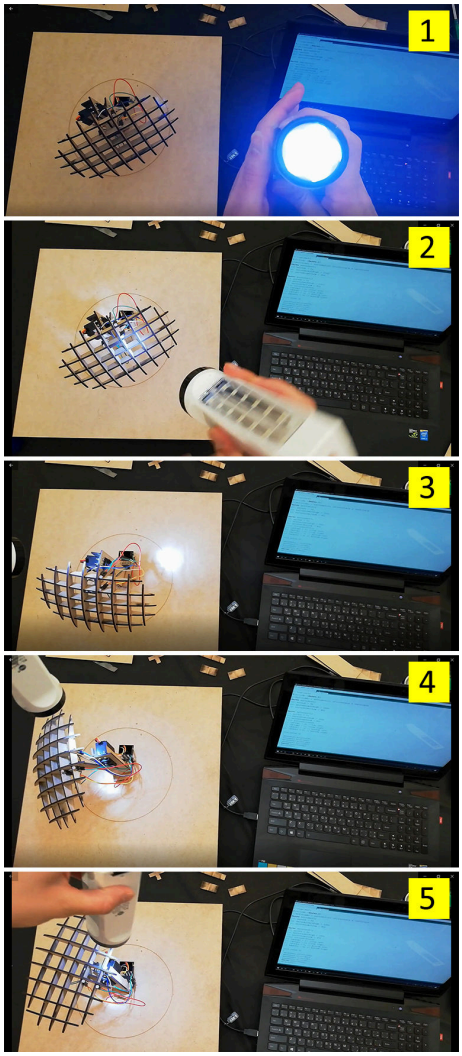



Figure 4
Prototype Mechanism [Authors]

```
set Servo_Horizontal to Horizontal
 ↪ ServoController
set Servo_Vertical to Vertical
 ↪ ServoController
set Sensor_TopLeft to Top Left Sensor
set Sensor_TopRight to Top Right
 ↪ Sensor
set Sensor_BottomLeft to Bottom Left
 ↪ Sensor
set Sensor_BottomRight to Bottom Right
 ↪  Sensor


set Servo_Horizontal.HighLimit = 150;
set Servo_Horizontal.LowLimit = 40;

set Servo_Vertical.HighLimit = 150;
set Servo_Vertical.LowLimit = 40;

function main()
{
    call setup function();
    loop {
        call mainLoop();
    }
}

function setup(){
    setup connection to servo
     ↪ controllers;
    wait 500 miliseconds; // Wait for
     ↪ initializing the servo
     ↪ controllers
}

function mainLoop(){
    servoh = Servo_Horizontal.
     ↪ ReadCurrentState();
    servov = Servo_Vertical.
     ↪ ReadCurrentState();

    avgtop = Average ( Sensor_TopLeft.
     ↪ value , Sensor_TopRight.value)
     ↪ ;
    avgbot = Average (
     ↪ Sensor_BottomLeft.value ,
     ↪ Sensor_BottomRight.value);
    avgleft = Average (
     ↪ Sensor_BottomLeft.value ,
     ↪ Sensor_TopLeft.value);
    avgright = Average (
     ↪ Sensor_BottomRight ,
     ↪ Sensor_TopRight);

    if (avgtop < avgbot)
    {
        Servo_Vertical.IncreaseOneStep
         ↪ ();
        wait 500 miliseconds //
         ↪ Waiting for servo to move
    }
    if (avgbot < avgtop)
    {
        Servo_Vertical.DecreaseOneStep
         ↪ ();
        wait 500 miliseconds //
         ↪ Waiting for servo to move
    }
    if (avgleft > avgright)
    {
        Servo_Horizontal.
         ↪ IncreaseOneStep();
        wait 500 miliseconds //
         ↪ Waiting for servo to move
    }
    if (avgright > avgleft)
    {
        Servo_Horizontal.
         ↪ DecreaseOneStep();
        wait 500 miliseconds //
         ↪ Waiting for servo to move
    }
}
```

## CONCLUSION

The ultimate result of the project demonstrates a HelioPhilia intelligent kinetic canopy which has reached the specified targets. A high level of interactivity is implemented for this structure in order to cover a great deal of space under the canopy to cast a shadow which provides thermal comfort and enough amount of passing light inside. Besides, as it is computational design, this system has to compute the amount of light that each sensor faced so as to locate itself directly in front of the sun light.

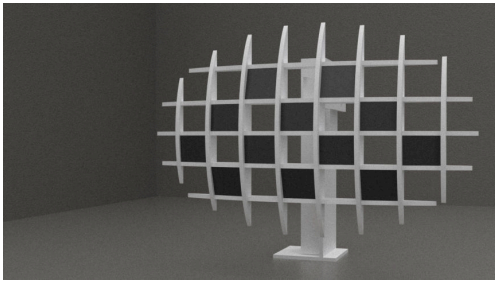


Figure 5
Sample of Installing Solar Panels on the Structure [Authors]

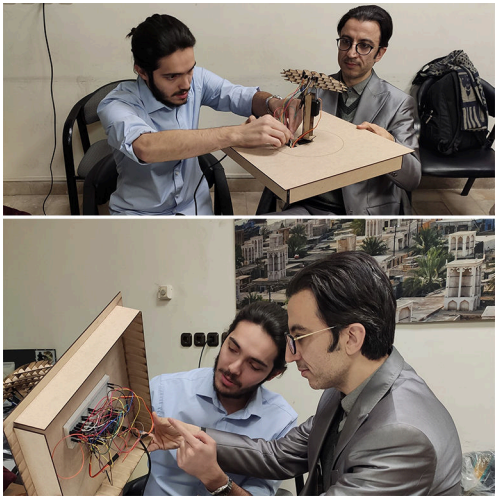


Figure 6
Final Prototype Examination [Authors]

A mechanism from nature with high-tech methods has designed. This research provides us a brand-new innovation by which users' comfort comes first. The outcome defines an unbounded potential for responsive and kinetic architecture which is intelligent to detect and recognize the light and itself transform the orientation due to meet users' needs. The built prototype define performance of the idea. This type of implementation determines the following merits:

- By using solar panels on the waffle frame spaces the canopy could be able to independently supply its energy. It would be completely sustainable with high efficiency.
- For future studies, it can be programmed to learn users' habits.

Unbound potential of intelligent architecture provides a new untouched field for contemporary and future architecture. The results of the research emphasized on prospect of potential ability on concurring between computational design and kinetic character of interactive monuments.

Consequently, developing kinetic architecture could happen with increasing the importance of thinking structures and other fields of study. Since they could lead designers to be more creative while they are using artificial intelligence to build more sustainable structures.

## APPENDIX

The programmed code :

```
#include <Servo.h>

//definition of the horizontal and
 ↪ vertical servomotors
Servo servohori;
int servoh = 0;
int servohLimitHigh = 150;
int servohLimitLow = 40;

Servo servoverti;
int servov = 0;
int servovLimitHigh = 150;
int servovLimitLow = 40;
```

```
//Photoresist pin
int ldrtopl = 2; //top left
int ldrtopr = 1; //top right
int ldrbotl = 3; // bottom left
int ldrbotr = 0; // bottom right

 void setup ()
 {

  servohori.attach(10);
  servohori.write(60);
  servoverti.attach(9);
  servoverti.write(60);
  Serial.begin(9600);
  delay(500);

 }

void loop()
{

  servoh = servohori.read();
  servov = servoverti.read();
  //Analog value of photoresistance
  int topl = analogRead(ldrtopl);
  int topr = analogRead(ldrtopr);
  int botl = analogRead(ldrbotl);
  int botr = analogRead(ldrbotr);
  // Let's calculate an average
  int avgtop = (topl + topr) ; //
   ↪ average of top
  int avgbot = (botl + botr) ; //
   ↪ average of bottom
  int avgleft = (topl + botl) ; //
   ↪ average of left
  int avgright = (topr + botr) ; //
   ↪ average of right

  if (avgtop < avgbot)

  {
    servoverti.write(servov +1);
    if (servov > servovLimitHigh)
     {
      servov = servovLimitHigh;
     }

    delay(10);
  }
  else if (avgbot < avgtop)
  {
    servoverti.write(servov -1);
    if (servov < servovLimitLow)
  {
    servov = servovLimitLow;
  }

    delay(10);

  }

  else
  {
    servoverti.write(servov);
  }

  if (avgleft > avgright)
  {
    servohori.write(servoh +1);
    if (servoh > servohLimitHigh)
    {
    servoh = servohLimitHigh;

    }

    delay(10);
  }

  else if (avgright > avgleft)
  {
    servohori.write(servoh -1);
    if (servoh < servohLimitLow)
     {
     servoh = servohLimitLow;
     }
    delay(10);
  }

  else
  {
    servohori.write(servoh);
  }

  delay(50);
}
```

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[1] http://www.achimmenges.net/?p=5922

# Occupancy-informed:

## *Introducing a method or flexible behavioural mapping in architecture using machine vision*

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*The feedback-loops of the modern architectural design practice are broken, as architects rarely get to experience and learn about life in their buildings in a systematic way. Through novel survey and annotation methods, this project aims to develop tools and methodologies that assist architects in getting insights into the built environment. This paper describes the initial development of a framework for surveying and annotating occupant behaviour within architecture, called ``Behavioural Situations''. Using object recognition on embedded devices, it is possible to build an understanding of occupant behaviour, by coupling behavioural signifiers and their relations as nodes and edges in a graph representation.*

**Keywords:** *Occupant behaviour, Behaviour sensing, Computer-vision*

### INTRODUCTION

Though architecture is a knowledge-based field (Schön, 1984; Visser, 2010) knowledge generation and design research rarely expands from the drawing tables and CAD software of the studios and into the world of finished buildings and living people. Despite the omnipresent calls for an increased focus on the potentials of human-centred and behaviour-driven insights for improving life in and value of buildings (Arup 2016, Sylvest 2017), the field is lacking technologies for mapping and analysing occupant behaviour that can directly inform the architectural design process.

The methods used for qualitative spatial analysis, have remained largely unchanged since the 1980s, (Jan, 1987; Gehl and Svarre, 2013b). Modern computational frameworks emphasise quantitative assessments of occupancy, with little regard to the qualitative and interactional aspects that are key to evaluating architectural spaces. Hence, the field is in need of new methods for understanding and analysing occupant behaviour in the built environment (Watson et al., 2015; Broch, et al, 2017). While the field has succeeded in developing computational tools, which integrate considerations for energy, light and other technical and physical aspects into design there are to our knowledge no computational methods for bringing dynamic behavioural considerations and data into the process.

In this paper we present the underlying framework and initial findings for the PhD research project "Sensing Behavior: Occupancy-Informed Architecture by Customisable Situational Mapping with Computer Vision". The project investigates the use of

computer vision on embedded cameras to create a novel behaviour aware notation framework, called Behavioural Situations. We explore technologies and frameworks for mapping, analysing and communicating occupancy behaviour within the built environment, with the goal of making architects capable of better understanding and reacting to the behavioural implications of their designs for current and future occupants.

## SENSING BEHAVIOR - STATE OF THE ART

### *Tools for digital occupancy analysis*

With increasing focus on obtaining deeper knowledge about occupant behaviour, the development is quickly pushed forward towards more capable and sophisticated tools and methods. With research showing how data-driven design processes are improving design and operations of buildings (Thomsen et al., 2015), occupant-sensing technologies must become essential for behavioural research within architecture. Information-rich descriptions of behaviour can support the development of design and visualisation tools, enabling the development of architecture with consideration for the interactions between occupants and architecture, based on factual observations of existing and similar interactions. However, overviews of current approaches to occupancy evaluation and data management in the built environment, points to a lack of efficient digital frameworks for flexible and efficient mapping of occupancy-behaviour. Current sensor frameworks emphasize the collection of occupant "presence", "counting" and "tracking" (Dong et al, 2018), but lacks methods for assessing more qualitative behavioural aspects of occupation. In the following chapter, we will discuss our suggested framework to accommodate these shortcomings.

### *Machine Vision as turnkey technology*

Most state of the art sensor-systems for tracking of occupants are relying on Machine Vision in one form or another. The rapid advances in Computer-vision have enabled recognition, classification and tracking of people, objects, and even activities. With the emergence of accessible machine learning tools in the 2010s, machine-learning and related practices quickly integrated into architecture (Tamke, M. et al, 2018). Access to cloud-based computing and the availability of a large number of machine-learning training sets, as well as the introduction of specialised machine-learning hardware accelerators, provide new possibilities for developing and deploying case-specific machine-learning tools on embedded devices.

Computer vision is already being utilised commercially and academically for occupancy analysis (Dong, B. et al, 2018; Stisen et al., 2016). Such systems are capable of counting and tracking occupants, producing data containing quantities, locations, height, and walking paths of occupants. Highly specialized, these systems are developed with Facility Management and Retail applications in mind, providing data on utilization and occupancy data, informing real-time and future decisions. These systems lack capabilities for mapping of occupant relations and interactions, and the hardware is costly, black boxed and does not allow for adaptation to situational data nor easy deploy-ability and project specific customisation. While Machine Vision can serve as a technological ground for advancing mapping of behavior in buildings, we find a lack in their underlying theoretical framework concerning both collection, storing and analysis. Their narrow focus makes a mapping of the breadth of human behaviour and interactions impossible.

### *Manual Collection of Behavioural Data*

While digital occupancy analysis tools are a recent development, observing occupant behaviour within the build environment is nothing new in itself and related techniques in terms of observation and notation are in use. Post Occupancy Evaluation (POE) is used to bridge the gap between social science, technical performance assessment, and design. But while proven frameworks for POE exist, these are labour intensive and difficult to scale (Sylvest, 2017).

Current collection of behavioural data primarily use methods developed by architects in the 1970s and 80's (Gehl, 2011). These manual, "systematic observations" (Gehl, 2011; Gehl and Svarre, 2013a) are conducted with human observers counting "people-oriented indicators" to collect information on specific areas of interest. Such methods have enabled architectural practices to inform their designs on specific occupant centric parameters and to design inclusive and behaviour-centric architecture. But due to the limitations of manual systematic observation methods, this data lacks socio-spatial granularity and temporal longevity (Dong, et al, 2018).

### *Synthesis and communication*

Annotation, and visualisation of behavioral data is crucial for communicating occupancy insights in architectural design (Hornbæk and Khan, 2011). Current multivariate visualisations rely on charts and heatmaps or geographical map-overlays using either photographs or site drawings (Cuttone, 2017). This approach requires expert knowledge and produces highly abstract two-dimensional and static views of inherently time based data. On-going research investigates the use of computer aided drawing- and game design environments (Breslav S, 2014; Yehuda, 2012; Hornbæk et al, 2011) in order to visualise complex behaviours in built environments. However, current methods are expert based, hand-tailored to specific cases and data. Building on these, the Behavioural Situations framework aims to research customisable, automated methods for extraction and visualization of behavioural architectural data.

## SENSING BEHAVIOUR - FRAMEWORK

Based on our analysis of state-of-the-art in occupancy sensing we find that three areas have to be developed to create a framework for mapping, analysing and communicating occupancy behaviour within the built environment :

1. a theoretical framework to understand behavioural situations
2. sensors, capable of registering behaviour efficiently and flexible while respecting privacy,
3. a notional System, including customisable, automated methods for extraction and visualization of behavioural architectural data d

In the following section we describe the three parts of the framework in more detail and describe how we implemented these in a first prototype of a sensor system using the behavioural situations framework, and finally discuss the considerations and and insights that occurred from these first explorations.

### *Behaviour as Actions*

In the context of this project, we use the term behaviour as a description of activities by occupants and inhabitants. With acknowledgement to the fact thatbehaviour is extensively studied and theorized upon in both the Social, Human and Medical sciences, this project apply the term to describe activities that cause, or are caused by, observable interactions. By understanding behaviour as consisting of interrelated actions, we also connect what we observe with the context that the actions exists in. Consequently, behaviour contains both actions, relations and context.

### *Behavioral Situations*

The goal of the Behavioural Situations framework, is to organise relevant behaviourally significant activities into human and machine readable data, reulting in comprehensible registrations of occupant behaviour. A behavioural situation describes observable and recordable occupant relations and interactions, that are used to categorise occupant behaviour (figure 1). Behavioural situations can be as straightforward as recording an occupant within a certain spatial context. Such a context could be a hallway, with the object, a person, moving though it. This Behavioural Situation is parsed as a **"moving"** or **"walking"** situation. Placing two occupants in the hallway, but moving alongside, creates a different situation, transforming the Behavioural Situation from a purely infrastructural behaviour to also include a social as-

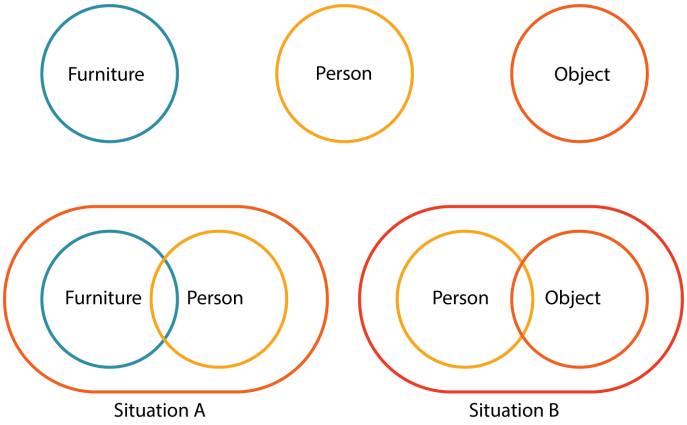



Figure 1
Behavioural Situations are defined by the objects they contain. Definitons can be based on predetermined categories such as Person + Chair = Sitting, but can similarily contain combinations of objects, without any category assigned.

pect, as we assume that occupants walking alongside will potentially be interacting with each other.

In addition to spatial relations, objects are also included in the behavioural situations, creating complicated complicated scenarios. A situation consisting of a sitting person (behavioural situation of person related to chair), a table and a laptop can be assumed to be a working situation. Replacing the laptop with food, will change the situation from a working situation to an eating situation. Adding context that is not directly observable, can add even more complexity to a Behavioural Situation. Environmental aspects such as temperature and precipitation, or indoor noise levels can be added, merging multiple data streams, potentially adding insights into behaviour, while also providing more queryable data for recalling situations containing specific signifiers and contexts.

### *Machine Vision*

Small, affordable cameras with embedded computing power are rapidly becoming available for both industrial applications and research. These devices are useful for hardware projects that are relying on image-based processing, but without the need for these solutions to be connected to, and reliant on, a computer to do process the images. The benefit of this sensor-type, is the possibility to implement machine vision directly into applications that would otherwise not be feasible because of either cost, mobility or size constraints. The Behavioural Situations framework relies on such technology, applying machine-learning based object recognition as the first step of data collection, making it it possible to quickly and accurately detect occupants and their position within the surveyed space. By training object-recognition networks on both occupants, objects and architectural context, it is possible to construct graph-based representations of occupant behaviour, containing both descriptions of occupant-occupant interactions, the interaction with the context (Sylvest, 2017), and descriptions of the context itself.

By using object recognition running directly on the cameras, it is possible to collect detailed information, while keeping data anonymized. Ensuring that all data collection is in line with data ethics and current privacy regulations (GDPR, etc) is crucial for the future of these systems (Hasselbalch, 2016). Within the AI research and industry communities the answer has been to create systems that implement "privacy by design" and "privacy by default" through approaches for anonymising or pseudonymomysing personal data immediately after collection (Stopczynski et al., 2014) (Breslav S, 2014).

Object attributes can be calculated with several

Figure 2
Experiments showing the author beng registered by multiple networks running in parallel. From left, Yolact, MiDaS, Densepose.

methods, with varying precision and efficiency. At the time of writing, the project are exploring multiple approaches to camera based occupant registrations. Exploring both commercial and open-sourced solutions, it is becoming clear that the methods can be grouped in 3 categories:

- 2d image, triangulation based location, using knowledge of camera position and generalised occupant heights, it is possible to calculate the position of the occupants on an estimated floor.
- 2d image, machine learning based location. Using machine learning networks, trained on 3d objects, it is possible to estimate object dimensions and location from 2d images. (Figure 2)
- 3d image, stereo camera, additionally with structured light, combined with 2d images, it is possible to both detect objects, and measure their precise location in space.

### *Notation Systems*

Building up behavioural situations as interconnected graphs, enabled information-rich descriptions of specific behavioural situations, to include granular information, that can be of interest in more open ended queries. Storing registrations occupants, objects and context as nodes and physical and contextual relations as edges, registrations are no longer comprised of lists of self contained behavioural situations, but instead of complex networks of situations, containing both descriptions of specific behaviours, as well as all situations sharing one or more traits with this situation. For a situation containing a group of 3 occupants, standing in the entrance during a rain shower at 16.45, the graph exposes all of the contained information as queryable, and will be available in any search, concerned with any of the individual objects. The aforementioned example could be imagined as an interesting finding, when looking at occupant flow, through the building entrance and its relation to patterns during different weather conditions.

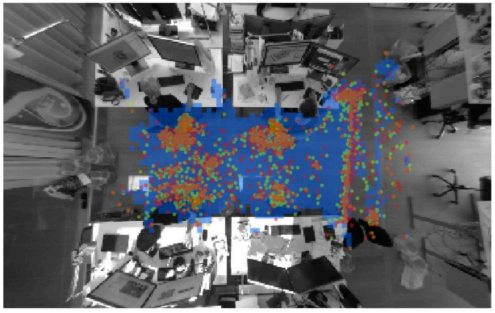


Figure 3
Captur from Xovis pc2 sensor, displaying occupant tracking through start and stop positions as well as heat map. The Xovis cameras track occupants based on stereoscopic cameras. As such, the sensor has both high precision and is capable of counting many occupants simultaneously.

### *Prototype experiments*

Serving as a starting point for this project, we developed a prototype, encapsulating the primary elements of construction behavioural situations on embedded hardware. Combining existing object recognition algorithms with custom code, the prototype detects behavioral significant objects, and combines these as graph representations. This prototype consisted of a raspberry Pi 3, equipped with a 160 degree fish eye camera (figure 4). To aid the rather limited computing power of the raspberry pi, it utilises a Intel Neural Compute Stick for increased processing power. The open source library Mobilenet-SSD

adapted for use with the Intel Compute Stick, because of its speed, and due to the fact that it's available with large training sets "out of the box".

Each detected object is the labelled with the object name, location and size. A secondary algorithm builds a graph from the objects, generating nodes for each object, and connecting nodes according to different rules on relations. Within the graph, object-nodes are spatially-related by existing within shared space, by being neighbouring and overlapping. Besides these spatial relations, nodes are also connected by belonging to similar functions (such as furniture, plants or computer equipment). During and after the survey, it is possible to search for Behavioural Situations, by querying parts of the graph for object nodes that are connected by spatial and functional relations.Searching through the created graphs, it is possible to build up an understanding of the surveyed space and the behaviour within. Such a search can focus on a quantitative assessment; how many "Chair" and "Person" relations were present at a certain point in time.

The first prototype was deployed in a cafeteria at the Royal Academy of Fine Arts, School of Architecture, Copenhangen. The semi-public environment, serving both as a public café, a student and employee socialising space and as study room, served as the test environment, with the primary focus being recognition and labeling of occupants activities.Running the prototype in the space,resulted in graphs describing Behavioural Situations consisting of solo occupants interacting with furniture and occupants moving though the space, without physical interaction with any of the environment (figure 5). Knowing the primary functions of the surveyed space, we can search the graphs for "studying" or "café guest", as these would both contain a person interacting with a group of furniture.

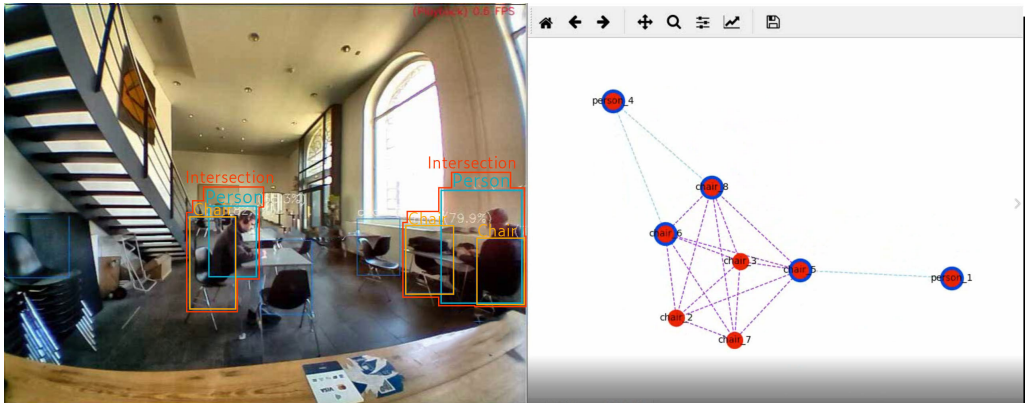
These first experiments demonstrate the feasibility in registering simple behaviour using object recognition on embedded devices, without the need for training the neural networks on images of every single relevant behavioural signifier. It becomes clear from the experiments, that camera placement is important in respect to obstructions as well as lighting conditions. While it is possible to use multiple cameras, tracking objects across multiple cameras demand a higher precision in setup and calibration. It is also evident that the training material, used to for the object recognition, needs to have sufficient relevant objects, to do rich behavioral registration. With only limited training sets, and subsequent objects, only shallow and information poor behavioural situations will be returned.

Figure 4
Prototype. Raspberry Pi 3 equipped with Intel Neural Compute Stick and wide angle camera.

## CONCLUSION AND OUTLOOK

Creating detailed registrations of occupant behaviour in architecture, will be able to benefit the architectural industry as a whole. While furniture and facade catalogues are easy to import into CAD software, and real-time rendering software allows the architect to instantly see the building with thou-

Figure 5
Output form initial prototype, shows the real-time construction of graph representations.




sands of different materials, no such thing exists for the occupancy. Simulation software exists, allowing architects to do Pedestrian Simulations within the buildings, but going further and collecting either real world data, or generalised models based on real world data will push the field further. Early experiments show that the framework behind behavioural situations already can effectively produce straightforward insights into occupant behaviour. Further development of the project will focus on strengthening the key parts of the framework, collection, analysis and visualization. Better camera based sensors, creating rich and deep graph representations of the life inside our buildings, will allow us to understand and design, with and for behaviour. Information-rich descriptions of the occupied environment, can support the development of design and visualization tools that will enable architects to develop architecture that takes the interactions between occupants and architecture into consideration, based on factual observations of real life behaviour.

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# D2.T8.S1. THE COGNITIVE CITY (AI)

# The Emoting City

## *Designing feeling and artificial empathy in mediated environments*

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*This paper presents a theoretical blueprint for implementing artificial empathy into the built environment. Transdisciplinary design principles have oriented the creation of a new model for autonomous environments integrating psychology, architecture, digital media, affective computing and interactive UX design. `The Emoting City', an interactive installation presented at the 2019 Shenzhen Bi-City Biennale of Urbanism/Architecture, is presented as a first step to explore how to engage AI-driven sensing by integrating human perception, cognition and behaviour in a real-world scenario. The approach described encompasses two main elements: embedded cyberception and responsive surfaces. Its human-AI interface enables new modes of blended interaction that are conducive to self-empathy and insight. It brings forth a new proposition for the development of sensing systems that go beyond social robotics into the field of artificial empathy. The installation innovates in the design of seamless affective computing that combines `alloplastic' and `autoplastic' architectures. We believe that our research signals the emergence of a potential revolution in responsive environments, offering a glimpse into the possibility of designing intelligent spaces with the ability to sense, inform and respond to human emotional states in ways that promote personal, cultural and social evolution.*

**Keywords:** *Artificial Intelligence, Responsive Architecture, Affective Computation, Human-AI Interfaces, Artificial Empathy*

## INTRODUCTION

Formalist approaches have dominated architecture for the past century, but have been criticized for a geometric rationality which distances the city from "the shapeless and dynamic acts of life and the ephemeral feelings evoked by architecture" (Pallasma, 2015). The introduction of ambient data-generating technologies such as sensors, wearables,

and personal robots in mediated environments creates the possibility of a new architecture, one with the power to perceive and elicit human emotions in non-anthropomorphic ways.

Currently, autonomous technologies are pervasive in cities, and have been used extensively to regulate human behavior. From medical wearables and robotic vacuums to digital thermostats, autonomous technologies operate in a continuous loop of monitoring, analysis, and feedback. Machine Learning (ML) will soon provide even greater autonomy through adaptive programming. The ability of autonomous systems to operate with no human intervention raises new design challenges and significant ethical concerns. These include unintended or aggravating behavior (Picard 2008) and issues surrounding risk and responsibility for that risk; exemplified by the controversy surrounding driverless vehicles and their safety. Furthermore, autonomous systems utilizing facial recognition are often designed in a way that objectifies, limits and seeks to control human behaviour in a way that contributes to skepticism surrounding their use (Gates 2011).

Figure 1
The Emoting City Design Installation. (© Credit Dalila Tondo )

This paper presents a theoretical blueprint for implementing artificial empathy into the built environment. 'The Emoting City', an interactive installation presented at the 2019 Shenzhen Bi-City Biennale of Urbanism/Architecture (Figure 1) represents an initial steps into this emerging field. The installation explores the possibilities of human-AI mediated self-empathy in environmental design. It also investigates the technical implementation of these concepts by proposing new architectural elements capable of artificial perception and the ability to express artificial empathy. 'The Emoting City' brings to light new modes of human-human and human-AI interaction that are emerging in the context of autonomous environments. It brings forth a new proposition for the development of spaces that go beyond surveillance systems and anthropomorphic designs coming from social robotics, and that move forward to innovate in the design of interfaces that are transparent and self-effacing and therefore conducive to seamless levels of interactivity.

By connecting emotion sensing software (McDuff et al, 2016) with kinetic architecture, 'The Emoting City's interactive model facilitates the design of new elements in the built environment which respond to the facial expressions of occupants using motion and colour as semiotic tools for the purposes of personal insight. By perceiving and decoding human emotions, it is possible to create environments which facilitate the integration of autonomous technologies in ways that radically expand what is possible within traditional formalist environments.

## CONTEXT

Empathy is defined as the ability to share someone else's feelings or experiences by imagining what it would be like to be in that person's situation. This definition is generally applied to human-human interaction but as we interact with non-human systems more and more the concept of empathy requires some modification to include human-AI interaction. Indeed, the role of human-AI 'empathy' in interactive design has never been so important. This modified application of Empathy has its roots in the concept of Cybernetics originally formulated by Norbert Wiener (Wiener, 1948), Pask's (1976) proposal for human-machine, teach-learn feedback in 'Conversation Theory', and is at the core of embodied interaction (Dourish 2001) and user-centred design (Black 1998, Woodcock et al. 2018, Wright & McCarthy 2008).

In the context of affective and aesthetic interactive experiences that blend human and artificial intelligences, our understanding of empathy acquires new connotations. Traditional approaches to empathy-based design have been focused on human to human empathy processes that rely on cultural and symbolic systems of emotion expression, perception and interpretation. Empathy among human actors is derived from audiovisual cues such as dialogue and expression, and depends upon a subjective interpretation that relies on a particular individual's ability to decode subtle signs of emotion such as tone of voice and facial expressions.

Human-human interactions that are empathic generate affective diversity and give origin to emotional bonds. However in the context of human-AI interactions, empathy becomes elusive. A different type of question emerges: can empathy exist in the context of human-AI interaction? If yes, how different is it from human-human interactions and what makes it unique? There are many initiatives currently researching possible answers to these questions.

Even though there are many current human-AI applications that are dedicated to creating new artificial empathy experiences, initiatives that address the design of embedded sensing capabilities in responsive environments with the specific purpose of promoting self-empathy and insight could not be found in our research for this project. 'Emoting City' is our response to this gap in human-AI interface design.

## EMBEDDED CYBERCEPTION

Cyberception is defined as "the convergence of perceptive and conceptual processes in which the connectivity of telematic networks plays a constructive role" (Cipolletta 2018). When considering environmentally embedded processes of AI, facial-recognition technologies present themselves as powerful tools for cyberception. However, these technologies have acquired a bad reputation for their use as social surveillance apparatuses (Gates 2011) that collect personal information that is unidirectional: it is farmed directly from individuals into the databases of institutions, however individuals have no access to their own information.

The potential facial-recognition systems show in the context of artificial empathy has been researched extensively by the futurist Pamela Pavliskac (2018, 2019), who has coined the term *Design Feeling* to refer to the new possibilities brought about by emotional artificial intelligence (McStay 2018). The term recognizes the increasingly interdependent nature of how technology affects human emotions and how emotion-detection informs the design of new affective technologies.

Design Feeling reinforces the vision for a transdisciplinary architecture that facilitates new experiences which connect virtual, environmental, corporeal, and psychological dimensions. This transdisciplinary approach to architecture has been well established by several seminal architects and artists. Ascott (1995) argues that the current state of western architecture does not support "the human need for transformation". Cyberception can enable a new form of architecture to support post-biological life, characterized by "artificially enhanced interactions of perception and cognition". This approach was pioneered by Derrick de Kerckhove (2002), who has connected Ascott's concept of cyberception as architecture directly to environmental applications of AI. The architecture of intelligence (de Kerckhove 2002) describes a two-way road bridging material levels of reality to cognitive levels of experience.

### *Architectural Precedence*

The interconnected relations between psychology, digital technologies and architecture are clarified by deCOi Architects in their seminal paper Technological Latency: from autoplastic to alloplastic (2000). This work marks the beginning of the application of digital sensing technologies to built environments to design transformative cognitive experiences. Embedded cyberception expands the transformational potential of architecture causing "a shift from an autoplastic (a self-determinate operative strategy) to an

alloplastic (a reciprocal environmental modification) mode of operation" (deCOi 2000).

Phillip Beesley and Mark Goulthorpe are two key architects who have sought to leverage emerging technologies to evoke and bring to light various psychological responses through their work. In "Hyposurface" (2003), Mark Goulthorpe designed a faceted metallic surface that deforms physically as a real-time response to environmental stimuli. The architect defines this work as "alloplastic" - a term attributed to Freud by Ferenczi (1994) to describe an individual's psychological attempt to adapt to a situation by changing their external environment. The concept of alloplastic adaptation [the outer-oriented adaptive response of an individual to a challenging reality] has been established in classical psychological theory in a parallel to autoplastic adaptation [the inner-oriented adaptive response to the same reality].

In his architecture, Goulthorpe enables the "possibility of a reciprocal transformation in which both subject and environment negotiate interactively" (Goulthorpe, 1999). In the context of embedded cyberception, processes of reciprocal transformation that are mediated by reflective surfaces presuppose an interplay between human and artificial empathy. Even though, from a classical psychological perspective, all transformational processes are initially autoplastic and originate from individual attempts of self-transformation, ultimately the result of autoplastic adaptation is to generate collective processes of alloplastic adaptation. Alloplastic social interventions come from "advanced technological societies" and "are generally characterized by 'alloplastic' relations with the environment, involving the manipulation of the environment itself" (Malmgren 1991).

Alloplastic adaptation in architecture has been connected to processes of broad cultural and social evolution (deCOi 2000, Malmgren 1991) that when mixed with digital technologies that allow real-time interactivity can simulate human empathy. Phillip Beesley is a strong example of alloplastic architecture, leveraging technology to simulate empathy in physical spaces. In his "Hylozoic Series", Beesley designs instability, fragility and weakness into the structural meshworks of the installations. By absorbing and dissipating environmental stresses, the structures inspire a new architectural lexicon. Beesley (2012) uses the words "shuddering", "resonating", and "oscillating" to describe the creation of a "felt space of empathy and exchange" in this work.

While these examples focus on alloplastic adaptation using real-time transformation and manipulation of environments to elicit and assess collective psychological responses, 'The Emoting City' focuses instead on autoplastic adaptation at an user's cognitive level, enabling processes of self-transformation that are based on artificial empathy generated by cyberception across reflective surfaces.

### *Layers of The Emoting City*

'The Emoting City' brings forward a multi-layered conceptual model that uses intelligent environmental design to create artificial empathy. It operates across three main layers of interactivity (Figure 2): 1. Computational, 2. Environmental and 3. Human. This simultaneous interactive layering of computational, environmental and human dimensions of experience embodies Ascott's concept of cyberception by creating moist environments that blend the dry dimension of technology and artifacts (AI, hardware, built objects) to the wet dimension of living multi-species (humans, plants, natural life).

- **The first layer** represents the dry computational part of interactivity and contains artificial technologies such as various kinds of AI systems: affective computing systems, data storage and processing, sensing, synthesis of automated behaviour.
- **The second layer** represents the moist tangible spaces that bring together physical artifacts and living non-human entities forming the threshold of interactivity. This layer is composed of a mesh of connected devices and elements which hunt and gather affective data from the environment and its inhabitants.

Figure 2
Figure 1. “The Emoting City ” conceptual diagram depicting applications and components across 3 layers: computational environmental, and human

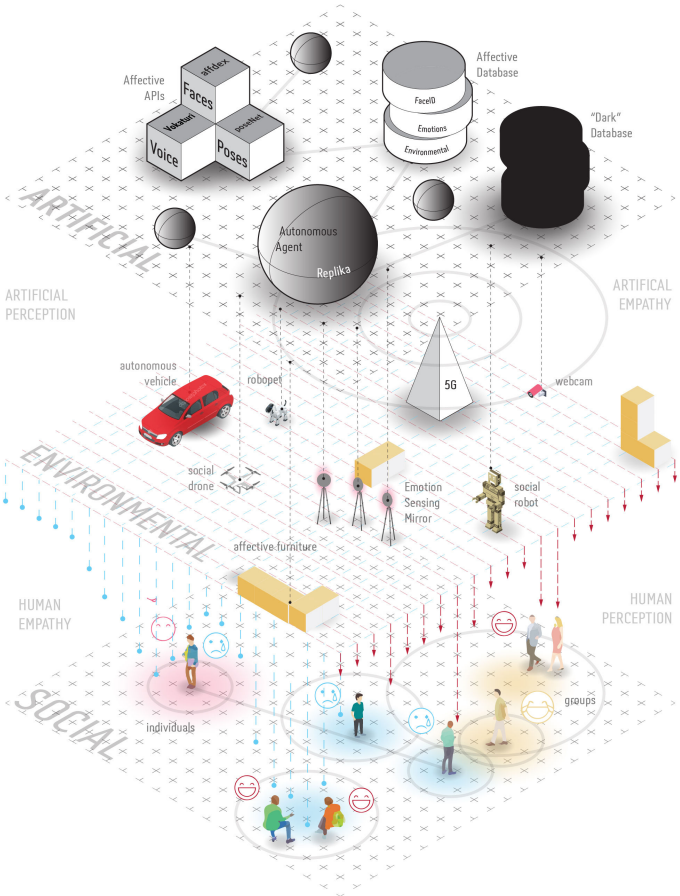


Figure 3
'The Emoting City' installation: an affective computing network of smart mirrors

- **The third layer** represents the wet dimension of human cognition, composed of neurological and psychological elements that determine the emotional meaning and transformational potential of interactivity.

## REFLECTIVE SURFACES

In the emerging research field of artificial empathy, human-AI interfaces have mostly been used to generate useful data for machine learning that aims to simulate human-empathic responses for the purpose of user engagement and therapy. Current research on artificial empathy has been restricted to machine learning systems that are trying to mimic human empathy in their user interfaces. This approach is unidirectional: human-AI interaction happens for the purposes of improving machine-simulations of human empathy. What we lack is a multidirectional approach to artificial empathy that leaves behind social robotics and moves forward into non-anthropomorphic embedded cyberception (Ascott 1995).

By placing robotic emotion-sensing mirrors in public spaces to reflect passerby's emotions back to themselves, 'The Emoting City' enables multidirectional cyberception (Figure 3: the information being sensed is reflected back to the individual user in an immediate and transparent way, and can be used to generate self-empathy and insight. This cyberceptive informational loop can then generate artificial empathy.

A network of robotic mirrors act as interactive surfaces that allow autoplastic emotional self-insight (Figure 4). The mirrors use visual cues to discern emotion states by analyzing a real-time video feed captured by an internal camera. We have used two real-time facial recognition toolkits to enable cyberception: AffdexSDK[2] and PoseNet [3]. AffdexSDK provides real-time facial coding of multiple human expressions. It is trained on the world's largest dataset of facial expressions (McDuff, 1996). It works by tracking facial features in order to determine facial actions (ie. smile, frown). The combination of facial actions are then used to infer seven categories of emotion expression (anger, disgust, fear, joy, sadness, surprise and contempt), to which it assigns a score from 0 to 100. PoseNet then complements this categorization and measuring with a Google-developed real-time machine learning model that performs human pose estimation (Papandreou et. al, 2018). PoseNet is able to detect and track the motion of the human body by decoding "key-points" from images and video.

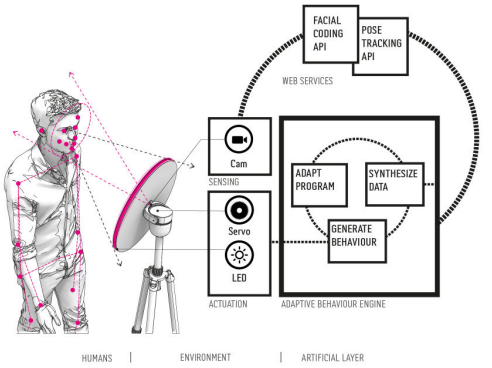


Figure 4
Cyberception informational loop facilitated by one mirror.

Figure 5
Layered (transparency and reflection) smart mirror in use. Self-empathy via facial tracking and color change. Infinity mirror effect is achieved through the superposition of two mirrors, whereby one-way film is applied to the front mirror, which creates a series of smaller and smaller reflections which recede to infinity.

The data collected from this apparatus of emotion sensing is then used to inform robotic responses using movement and light. Robotic movement mimics an user's motions at the same time as the user receives visual stimuli from different colored lights that match the user's facial expressions to a colour cate-

gory based on emotions. A pan-tilt mechanism allows each mirror to swivel in two axis, providing the ability for the robot to perform mimicry of body gestures; a common approach applied in social robots to elicit responses in users (Shazwani et al, 2019). In addition, seeing their emotions decoded visually generates emotional self-awareness which in turn brings about a process of artificially-mediated self-empathy. Therefore, 'The Emoting City' is able to connect mimicry-based empathy to reflective processes of self-empathy. In human societies, it is common for individuals to mimic the facial expressions of others to communicate empathy, preference and affiliation. The mirrors elicit responses from people using gestual mimicry and improves processes of self-awareness by using colored light and motion as emotional tools for self-insight. Because the mirrors do not possess anthropomorphic embodiments, we chose to use color as a visual reflection of emotional states. This decision was based on the observation that human subjects do tend to consistently ascribe the relative amount of redness and yellowness in a face (defined along the two colour axes of CIELAB color space) to the exemplars of six classic emotion categories (Thorstenson, Elliot, Pazda, Perrett and Xiao, 2018).

By focusing on environmental-based artificial empathy experiences and mediated individual processes of self-insight, this approach contrasts other developments such as social robots. Unlike most social robotic applications that use anthropomorphic embodiments to simulate human communication processes, and other virtual implementations of emotion sensing that aim to mirror emotional states by mimicking human empathy, we do not try to give a human likeness to AI (Figure 5). We move beyond the anthropomorphic mimicking of human emotions by social robotics into using environmental robotics as self-effacing surfaces that can decode and replicate a user's emotions for the purposes of self-empathy and personal insight.

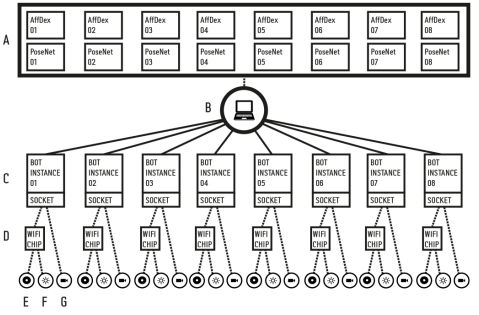


Figure 6
Cyberceptive architecture of 'The Emoting City'. [A] API Service Layer sends video data to ML models for facial coding and human pose estimation. [B] A laptop is used as a mobile server hub. [C] Multiple instances of the "Bot" program can be launched on the client side web-application. [D] ESP8266 WIFI Microprocessor connects to the laptop wirelessly through a web-socket. [E] Servo Motor to control pan-tilt mechanism. [F] Led strip [G] WIFI camera

## CYBERCEPTIVE ARCHITECTURE

The cyberceptive architecture of the emoting city installation is illustrated in figures 6 and 7. The software, hardware, and social components of 'The Emoting City' have been designed to be deeply intertwined and able to function, adapt, and scale to changing spatial and temporal dimensions. A custom web-based application was developed to be run on a high-performance laptop, through a local NodeJS server. On the back-end, each mirror uses two SDK's to support artificial perception. Firstly, PoseNet provides human pose tracking, returning key points on the human face, such as the eyes and nose. Secondly, Affedex provides facial coding and maps facial expressions to human emotion states. The software architecture is configured to simultaneously run multiple instances of the mirror program asynchronously. In each instance, face position and expression data captured by the webcam are translated into dynamic motion and lighting behaviours. Using WiFi WebSockets, the computer communicates unique instructions to each mirror.

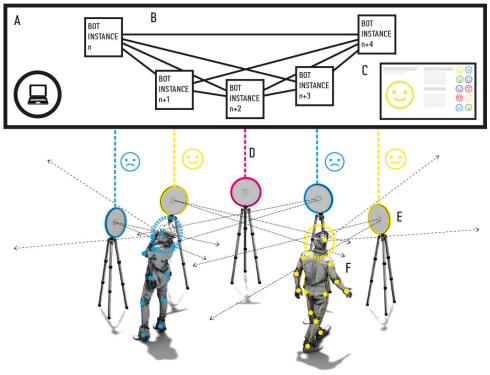


Figure 7
Distributed Cyberception as network. [A] Local server. [B] Multi-directional communication between program instances [C] Data dashboard and visualization

### *Robot Assembly*

Figure 8 describes the assembly of each mirror. They are designed with an automated pan-tilt mechanism composed of 3d printed as well as off-the-shelf components (see Figure 3). Each assembly is equipped with a SQ11 micro-usb camera (J) for facial recognition and a 1.5m WS2812B RGB LED strip (0) to display the colors in relation to the emotions. The assembly is designed to be mounted on generic tripods using a 1/4"-20 D socket (G). The pan-tilt mechanism is governed by two 15kg torque servos (B,H). Both servos and LED strip are powered by an external 5 Volt power adapter. The movement and LED color of each mirror is controlled by an ESP8266 wi-fi module (F) connected to a central WIFI-hub. Additionally, the pan-tilt mechanism hosts the "smart mirror" consisting of two 1mm thick round acrylic disks (L,P) covered with a one-way mirror film. The disks sandwich the LED strip at the perimeter pointing inwards with a spacer (N), creating the infinity-mirror illusion once activated. The infinity mirror assembly is directly attached to the tilt bracket (K) through an opening, and fastened by two 3mm screws from the back to a 3D printed fastener (M).

### *Adaptive Behaviour*

Each mirror is encoded with the ability to change its behaviour based on the surrounding context. Distance is estimated by calculating and comparing the pixel distance between facial features. The mirrors apply intelligence to modulate levels of interactivity based upon oscillations in the number of users in a given environment. When their context is crowded, and multiple faces are identified, the mirrors can limit the distance in which faces will be tracked and analyzed. When there are few users around, the mirror either enters a sleep mode assuming a neutral color (search mode), exhibiting a continuous pre-set motion pattern in order to try to find new users and encourage engagement.

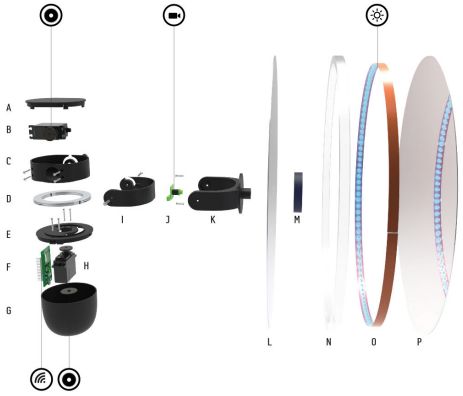


Figure 8
Exploded view of automated pan-tilt mechanism and infinity mirror

Over the course of the day, and responding to variations in user flow and movement, the behaviour of the robots oscillates between "shy" or "extroverted" modes of operation. When operating on "extroverted" mode, the mirrors actively seek out interaction with human faces. When operating on "shy" mode, each mirror assumes an avoidance behaviour, moving in an opposite direction in relation to the user, encouraging a higher level of engagement from the user.

## CONCLUSION

'The Emoting City' explores the emerging field of artificial empathy (McStay 2018) in the context of environmental design and alloplastic architecture. The conceptual inquiry and technical approaches dis-

cussed here set the stage for future research to investigate new applications to create elements and systems which imbue the physical environment with two main abilities: [1] Embedded Cyberception that senses human emotional states, and [2] Reflective Surfaces that modify their function and behavior in response to them. These two modes of interaction are autoplastic, eliciting inner-oriented adaptive responses based on an individual's awareness of their own emotional states. Because this self-awareness takes place via an artificially-mediated process of self-empathy, we classify it as artificial empathy in responsive environments.

Therefore, the Emoting City experiments with the creation of responsive environments that are embedded with dynamics of artificially-mediated emotional intelligence that could, among other capabilities, be used as inputs to processes of self-insight and self-empathy. Our design proposition represents a radically new approach to mixed realities: one that folds and inflects the alloplastic architecture of an environment into the autoplastic interior spaces of human experience. By blending environmental design and artificial empathy, we push forward the boundaries of human-AI interfaces beyond the constraints of simplistic applications of machine learning that disregard the complexities of human cognition.

### *Limitations and Next Steps*

Our main limitation in this approach is related to the highly complex nature of human emotions. While facial expressions are important cues for human-human interaction, humans rarely focus solely on facial expression alone for emotion recognition (Planalp, DeFrancisco, & Rutherford, 1996). Emotional communication varies significantly depending on different dynamics and levels of understanding between person to person, culture to culture and situation to situation. To further complicate things, a given configuration of facial movements can express more than one emotion category, given that emotions can be intertwined with each other in ways that are hard to categorize.

Humans process information based on their surrounding context and recognize emotions in an integrated manner (Barrett, Lindquist, & Gendron, 2007; Masuda et al., 2008). As a result, this work can be improved by continuing to explore and develop new systems to engage a wider range of sensory modalities tied to emotion beyond facial movements, such as voice prosody (Larsen et al, 2008) and body movement. To achieve this, multisensory increments can be added to future iterations of the mirrors.

An initial idea for technical innovation would be to incorporate auditory elements for emotion perception and elicitation (Larsson et al., 2009). The auditive feature would include earcons devoid of emotional meaning (noise and tone complexes) rather than identifiable sounds to give the mirrors their own unique identity, detached from any association with real-world entities. In fact, the ability of non-musical and non-vocal sounds to induce emotions is proven by research (Todd 2001, Vitz 1973), with the latter being associated with a pleasant-unpleasantness dimension of experience (Wundt 1924). Beyond expanding sensing capabilities to afford multisensory data processing, a further avenue for experimentation would be to integrate autonomous intelligent agents such as therapeutic bots (ie Replika) to the devices.

### *Questions for Further Research*

If intelligent machines can learn how to simulate human empathy based on human-AI interaction, what can humans learn about their own selves when interacting with AIs? How can we build autoplastic environments? Can human-AI interactions serve as mirrors to evaluate how humans can achieve higher levels of self-empathy? If yes, what would be the ethical and psychological implications of designing responsive environments that can sense, reflect and influence emotions?

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# Automatic Generation of Horizontal Building Mask Images by Using a 3D Model with Aerial Photographs for Deep Learning

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*Information extracted from aerial photographs is widely used in urban planning and design. An effective method for detecting buildings in aerial photographs is to use deep learning for understanding the current state of a target region. However, the building mask images used to train the deep learning model are manually generated in many cases. To solve this challenge, a method has been proposed for automatically generating mask images by using virtual reality 3D models for deep learning. Because normal virtual models do not have the realism of a photograph, it is difficult to obtain highly accurate detection results in the real world even if the images are used for deep learning training. Therefore, the objective of this research is to propose a method for automatically generating building mask images by using 3D models with textured aerial photographs for deep learning. The model trained on datasets generated by the proposed method could detect buildings in aerial photographs with an accuracy of IoU = 0.622. Work left for the future includes changing the size and type of mask images, training the model, and evaluating the accuracy of the trained model.*

**Keywords:** *Urban planning and design, Deep learning, Semantic segmentation, Mask image, Training data, Automatic design*

## INTRODUCTION

### *Background*

Information extracted from aerial photographs is widely used in urban planning and design. For example, green coverage rate and sky factor can be measured and building location and exterior can be confirmed from photographs. As the use of unmanned aerial vehicle (UAV) technology has become more widespread, aerial photographs have become easier to take. Information that requires real-time properties, such as damage to buildings during a disaster, can be grasped using aerial photographs taken by UAVs. To obtain highly accurate information, it is necessary to capture many photographs in a short period of time. An effective method for detecting buildings in aerial photographs is to use artificial intelligence for understanding the current state of a target region.

Recently, methods have been proposed for object detection and segmentation by deep learning. These methods can quickly and automatically detect the target objects in an image. It is also possible to detect buildings in aerial photographs by using this method. The accuracy of building detection is greatly influenced by the quantity and features of the dataset used to train the model, and it is necessary to train the model adequately for each target area. However, the building mask images used to train the model are generated manually in many cases. Considerable time is required to generate mask images from aerial photographs for model training because one aerial photograph can contain many buildings and many sets of aerial photographs and mask images are needed to train the model. A lot of image editing software is available, such as Adobe Illustrator [1] and GIMP [2]. This editing software has a function for automatically clipping target objects. The function is effective when the colour of the target objects and background are different. However, if the colours of some buildings are similar to the ground, the auto-clipping functions are not effective for generating specific mask images.

To solve this challenge, a method is proposed for automatically generating mask images of buildings, roads, and other objects by using virtual reality (VR) 3D models for deep learning. Mask images can be easily generated by using 3D virtual models that are divided into objects such as buildings, roads, and terrain. Since the appearance of a normal virtual model is similar to but not the same as a photograph, it is difficult to obtain highly accurate detection results in the real world even if the image is used for deep learning training. A method is also proposed for generating label images by using aerial photographs and map information (Chen et al. 2018). In this research, we aim to improve the representation of the VR models by using textured aerial photographs on 3D models. The proposed method can automatically generate mask images by using these VR models and can prepare proper datasets. This can improve its capabilities to detect buildings in similar areas.

## *Previous research*

In recent years, many object detection and segmentation methods have been proposed that use deep learning. By providing training data, features are automatically calculated and objects are detected based on the calculated features. Methods that detect objective areas as rectangles in images by using a convolutional neural network (CNN) such as AlexNet (Krizhevsky et al. 2012) and You Only Look Once (YOLO; Redmon et al. 2016). Semantic segmentation (Long et al. 2015) classifies each pixel into several categories and segments the objects in images by the silhouette. A system of automatically calculating green coverage rate and sky factor by semantic segmentation (Cao et al. 2019) has also been developed. However, semantic segmentation methods cannot detect targets as objects of the same class. Instance segmentation (Dai et al. 2016) classifies each pixel into several categories in each object and segments the target objects individually. A deep CNN-based method for automatically detecting suburban buildings from high-resolution Google Earth images has been proposed (Zhang et al. 2016) as a building detection method using deep learning. A fused fully convolutional network model has been proposed to perform building segmentation (Bittner et al. 2018). Some research is being done to improve the accuracy of Mask-R-CNN for detecting building footprint boundaries. A method combining Mask R-CNN with building boundary regularization (Zhao et al. 2018) has been presented. A method for detecting different scales of building and segmenting buildings to have accurately segmented edges (Zhou et al. 2019) has been proposed. However, the building mask images for training the model are generated manually in many cases, which requires considerable time and expense to build.

To solve this challenge, a method has been proposed for automatically generating mask images of buildings, roads, and other objects by using VR 3D models for deep learning (Fukuda et al. 2019). By using the 3D virtual model, we can create datasets that include mask images easily and rapidly. Since normal

virtual models do not have the realism of a photograph, it is difficult to obtain highly accurate detection results in the real world even if the image is used for deep learning training. High-precision rendering methods have been developed, but it is generally difficult to use such methods because many computers do not have high enough specs. Using textured 3D models with photographs can solve this challenge.

### *Objective*

The objective of this research is to propose an automatic generation method for horizontal building mask images by using 3D models with textured aerial photographs for deep learning. Specifically, we aim to improve the representation of the VR models by using textured aerial photographs on 3D models. The method can automatically generate mask images by using these 3D models and can prepare datasets suitable for deep learning training.

## PRELIMINARY EXPERIMENT

In preliminary experiments, the proposed model was trained by using an existing dataset. U-Net (Ronneberger et al. 2015) was used in the proposed method because it detects objects accurately in pixel units for segmenting buildings in aerial photographs. The dataset for training was SpaceNet [1], which includes satellite images and ground-truth building footprints in Rio de Janeiro, Vegas, etc. Our proposed method used the dataset of Rio de Janeiro because it has the most building labels (polygons) among the six datasets.

Because the satellite images of SpaceNet are too large (19584 px×19584 px) for training the model, we divided the original images into 6940 small images (438 px×406 px). The model was trained on U-Net by using ground-truth images of the building and satellite images.

The accuracy of the model was then evaluated. For verification, Intersection over Union (IoU; Everingham et al. 2015) was used, which is a metric that evaluates how similar predicted areas are to the ground truth. IoU is given by Eq. (1) (Table 1).

$$IoU = \frac{TP}{TP + FN + FP} \tag{1}$$

Table 1
Confusion Matrix

| | Truly relevant | Truly non-relevant |
|---|---|---|
| Coded relevant | TP (True Positives) | FP (False Positives) |
| Coded non-relevant | FN (False Negatives) | TN (True Negatives) |

The results for building detection in aerial photographs in the test class by the trained model are presented in Figure 1 (left). The red areas are the predicted and true areas of buildings. IoU was 0.602 as calculated using the sets of aerial photographs and masksimages in the verification class of SpaceNet.

The results for building detection in aerial photographs in Sakaiminato City by the trained model are shown in Figure 1 (right). The cities in the ex-

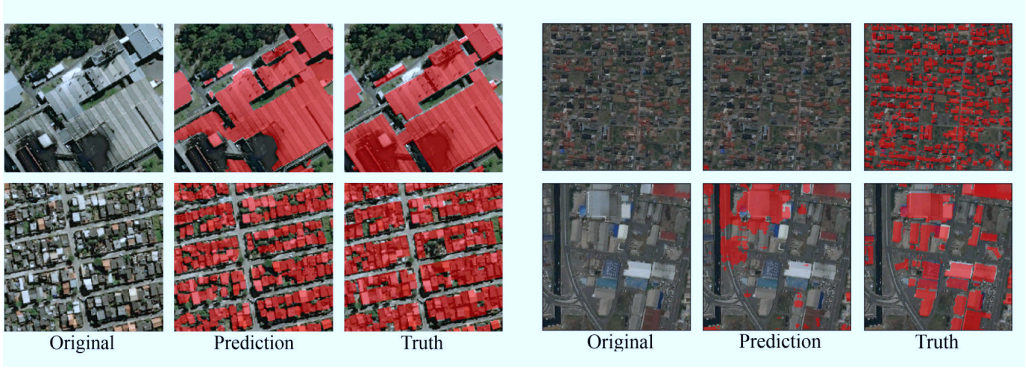



Figure 1
Results of detecting buildings on test photographs (left) and Sakaiminato photographs (right) by using existing dataset

isting dataset are densely built-up areas and have a low percentage of ground surface in the picture. On the other hand, in Sakaiminato City, there are several small-sized buildings, and the proportion of the land surface is large. IoU was 0.047 as calculated using the sets of aerial photographs and masks images in Sakaiminato aerial photographs.

The model trained by using the existing dataset detected buildings in aerial photographs in the existing dataset with an accuracy of IoU of 0.602. The IoU of this system exceeds the threshold value (IoU = 0.5) (Jabbar et al. 2017), meaning that the system can detect buildings sufficiently well. However, there are some over-detected and undetected buildings in the detection results in the target aerial photographs. There are two reasons for these problems. First, the colour tone of aerial photographs in the dataset used to train the model differs significantly from the target aerial photographs. Second, there are few vacant lots and farms in the aerial photographs in the Rio de Janeiro dataset whereas Sakaiminato City has many of these. It is necessary to consider these factors for building segmentation in rural cities that have many vacant lots and farms. The models need to be trained using datasets in areas that contain sevelal types of small and medium-sized buildings and a high percentage of ground surface.

## PROPOSED METHOD

Our proposed method automatically generates building mask images. The generated mask images are used to train the deep learning model for semantic segmentation. The proposed method loads 3D models that include terrain and building objects, classifies the building class and others class, switches between a model with all objects and a model with only buildings, and generates two upper view images of the models from multiple viewpoints. This system can generate multiple sets of mask images and aerial photographs from one 3D model. A conceptual diagram and flowchart for generating the dataset are shown in Figures 2 and 3, respectively.

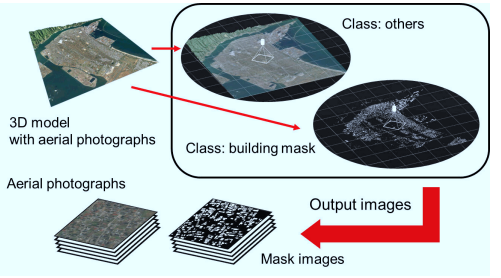



Figure 2
Conceptual diagram of generating mask images

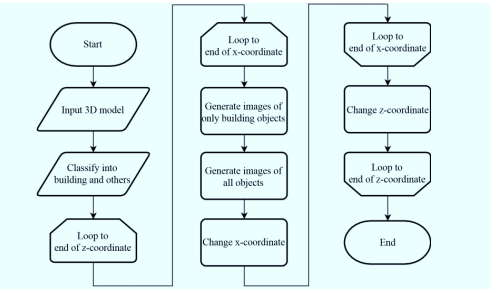



Figure 3
Flowchart of generating mask images

## PROTOTYPE SYSTEM

A prototype system was constructed to verify the accuracy of the dataset generated by our proposed method. The libraries and software for detecting buildings on aerial photographs are shown below. The OS of the PC is Ubuntu 16.04 LTS.

- TensorboardX 1.6

TensorboardX has an application programming interface (API) for determining the loss output during training in real-time. This was used to confirm the training state of the model.

- Jupyter Notebook

Jupyter Notebook is an analytical tool. It can simultaneously manage programs, explanations, and execution results. It was used to output the segmentation results.

The libraries and software for automatically generating sets of mask images and aerial photographs are shown below. The OS of the PC is Windows 10 Education 64-bit.

Figure 4
System to generate sets of aerial photographs and mask images

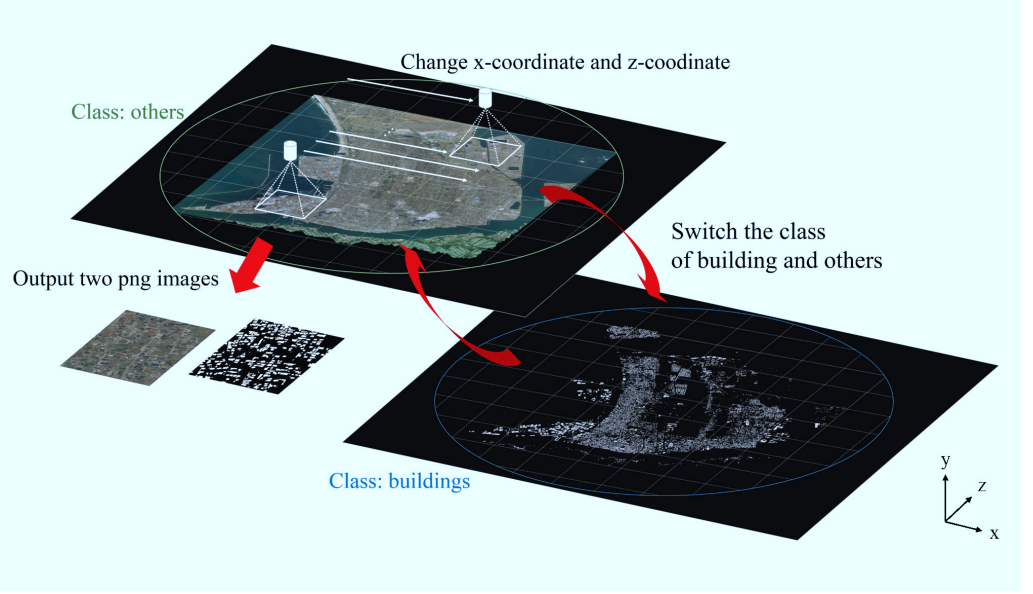



Figure 5
The 3D model created by Infraworks

- Autodesk InfraWorks 2019

Autodesk InfraWorks is infrastructure design software that can automatically overlay the textured images on the 3D model. It was used to create 3D models of the target areas.

- Unity 2017.3.1f1 (64-bit)

Unity is a game engine that can load 3D models. It was used to build systems to generate datasets.

Figure 4 shows the conceptual diagram of the system for automatically generating sets of aerial photographs and mask images. Our proposed system can automatically generate datasets from the 3D models input into the system.

The 3D model of the target areas was generated by using Autodesk InfraWorks. The building placement was determined according to Fundamental Geospatial Data (FGD) [4] provided by the Geospatial Information Authority of Japan (GSI). The aerial photographs are pasted on objects of the terrain. The generated 3D model is shown in Figure 5.

Table 2
Classification of objects in this system

| Objects | | Types | Classes |
|---|---|---|---|
| Object 1 | | Building | Building masks |
| Object 2 | | Road | Others |
| Object 3 | | Water | |
| … | | … | |
| Object N | Mesh a | Terrain | |
| | Mesh b | Terrain | |
| | … | | |
| | Mesh n | Terrain | |
| | … | | |

The objects in the model were classified into building objects and others in Unity (Table 2). We defined a camera for taking images of the 3D model. The x and z-coordinate of the camera were changed in steps of 100 over an area of 5600×5200 (world coordinates of Unity). The camera output images include only aerial photographs and images only building masks as png files (400 px × 400 px).

The number of datasets that can be created is insufficient when the target areas are small. In this case, it is necessary to use data augmentation methods. This system makes four images from one original image to increase the sets of aerial photographs and mask images. The original image is rotated 90, 180, and 270 degrees (Figure 6). The four images taken from the same camera position are used in the dataset.

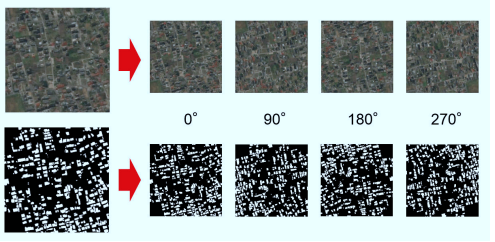



Figure 6
Data augmentation (rotation)

## RESULTS

### *Automatic generation of mask images*

The sets of aerial photographs and mask images automatically generated by our proposed system are shown in Figure 7. The middle column shows automatically generated mask images by the prototype system and the right column shows manually generated mask images. The white areas show the building mask. Our prototype system could generate 2912 sets in 190 s.

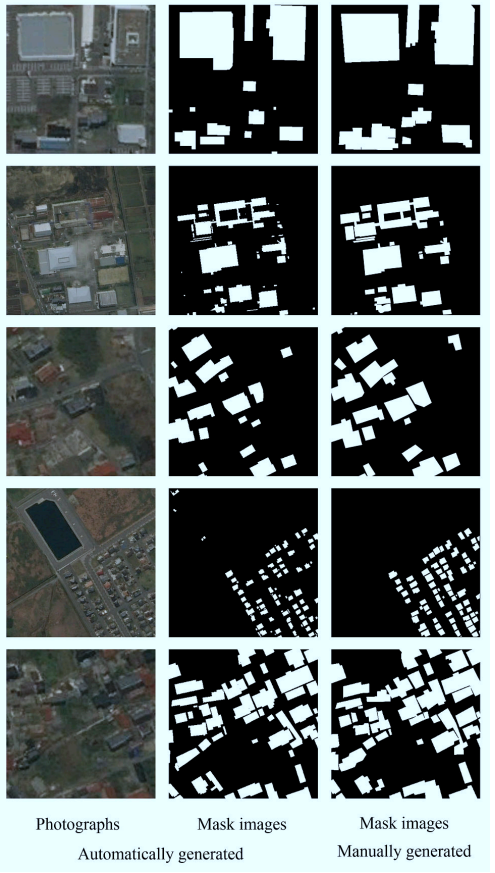



Figure 7
Generated aerial photographs and mask images

### *Building segmentation by using our trained model*

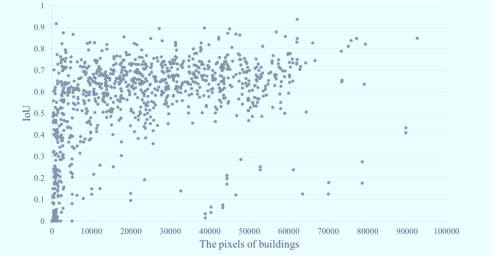
The results of detecting buildings in aerial photographs in the test class by our trained model are shown in Figure 8. The middle column shows the prediction results of our trained model and the right column shows the true results. The red areas are the predicted and true areas of buildings.

Figure 8
Results of detecting buildings on Sakaiminato photographs by using our trained model

Table 3
IoU of the trained model

| Training datasets | Objective area | IoU |
|---|---|---|
| SpaceNet (Rio de Janeiro) | Rio de Janeiro | 0.602 |
| SpaceNet (Rio de Janeiro) | Sakaiminato | 0.047 |
| Automatically generated datasets by our proposed system | Sakaiminato | 0.622 |

Figure 9
The detection accuracy of each image




## DISCUSSION

### *Automatic generation system*

Our prototype system generated 2912 sets of aerial photographs and mask images in 190 s. The time to generate the mask images was reduced by automatically generating them from 3D models in comparison to the manual generating method. The mask images generated by our prototype system are almost the same as the mask images generated manually. This system can generate mask images with detailed shapes. However, it cannot generate mask images of small warehouses. It is necessary to prescreen the generated mask images. By using a 3D model with aerial photographs, this system can be used for photographs taken from various angles.

### *Accuracy verification*

We trained the model by using automatically generated mask images by our prototype system and evaluated the accuracy of the trained model. IoU was calculated for accuracy verification using 1388 test images that were not used for training. The IoU of our trained model was 0.622. The accuracy of the SpaceNet model and our trained model are compared. We train each model by using the same number of mask images and evaluate the accuracy of the trained model for segmenting buildings in aerial photographs of Sakaiminato City. The accuracy of our trained model was better than that of existing datasets (Table 3).

Figure 9 shows the detection accuracy of each image. In many of the images with an IoU of 0.3 or less, the building was obscured by emissions from a factory. Inaccuracy was high in images where buildings were a low percentage of the total image. This model cannot easily detect small buildings, such as those in depopulated areas. One of the reasons for this is that the scale of the image is set according to the size of a general office building or factory.

## CONCLUSION

The conclusions of this study are listed below.

- A method was developed for generating sets of aerial photographs and mask images from 3D models with textured aerial photographs.
- Our prototype system can generate datasets more quickly than manual generation.
- The model trained datasets generated by our prototype system can detect buildings on aerial photographs with an accuracy of IoU = 0.622.

Work left for the future includes changing the size and type of mask images, training the model, and evaluating the accuracy of the trained model.

## ACKNOWLEDGEMENT

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# Topological Queries and Analysis of School Buildings Based on Building Information Modeling (BIM) Using Parametric Design Tools and Visual Programming to Develop New Building Typologies

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*School buildings are currently one of the largest portions of planning and building projects in Germany. In order to reflect the continuous developments in school building construction with constantly changing spatial requirements, an approach to analyse, derive and combine patterns of schools is proposed to adapt school typologies accordingly. Therefore, the topology is analysed, concerning interconnection methods, such as adjacency, accessibility, depth, and flow. The geometric analysis of e.g. room sizes or spatial proportions is enhanced by including grouping of rooms, estimated room clusters, or room shapes. Furthermore, text-matching is used to determine e.g. room program fulfilment, or assigning functional room descriptions to predefined room types, revealing huge differences of terms throughout time and architects. First results of the analyses show a relevant correlation between spatial proportion and room types.*

**Keywords:** *school building typologies, building information modeling (BIM), artificial intelligence (AI), topology, spatial analysis, digital semantic model*

## INTRODUCTION

The development of architecture is characterised by continuous change due to social, ecological and technological conditions. Contemporary and future building tasks take place against the background of the change of these framework conditions. The change in formal language of architecture, because of industrialisation and composite building material, resulted in classical modernism, with representatives like Le Corbusier or the Bauhaus, as the starting

point of the design methodology movement (Richter 2010).

The ideas of classical modernism in architecture and novel scientific and computer-aided methods led to the first generation of the design methodology movement in the 1950s and 1960s, e.g. represented by Christopher Alexander or Niklas Luhmann. In the 1970s the second generation of the design methodology movement, represented by Horst Rittel and others, did not view design procedurally as the fulfilment of requirements, but rather as an individual process that could only be described incompletely (Richter 2010). In the 1980s, the digital approaches of case-based reasoning (CBR) influenced the digital building design approaches, which led to the rise of a field of AI research in the building industry, called case-based design (CBD), in the 1990s. Even though at a current perspective the systemisation of complex cases in architecture is not sufficiently solved and is referred to as data acquisition bottleneck. For the formalisation of building information, object-oriented approaches (Eastman 1999) of product data modelling have been transferred to the construction industry in the 1990s. To remedy these shortcomings, Langenhan (2010, 2013, 2017) introduced the approach of "semantic building fingerprints" that facilitates spatial relationships and their digital processing based on enriched digital semantic building data. The digital semantic fingerprint of buildings was introduced to describe the main features of the design, forming the basis for similarity assessment to deal with ambiguities and complexities of architecture.

After major school building construction activities at the beginning of the 20th century and in the 1970s, Germany is now experiencing a third wave of school construction (Wenzel 2019). The renovation backlog of existing buildings and the current population growth requires school expansions and new buildings for all age groups and levels of education. The influx into conurbations is aggravating the situation regionally. In addition to the number of pupils and the necessary capacities, other use-specific changes demand structural quality and flexibility of contemporary school buildings, e.g. for all-day schools, for which the buildings designed as half-day schools are insufficiently designed. Moreover, new pedagogical concepts for integration, inclusion and digitalisation require new floor plan typologies, while considering old or constant requirements, such as large simultaneous circulation of people. While these old and new requirements are partly contradictory, schools are currently being designed in elaborate planning processes to develop new functioning building typologies. Therefore, new functioning building typologies have to be developed, while understanding and classifying existing facilities.

## PROBLEM STATEMENT

The amount of school building constructions, renovations, and expansions has constantly increased (Freireiss and Commerell 2019). Throughout history, schools, being the educational space, are a mirror of the economical essence and ideal of the current economy (Schmidt and Schuster 2014) by shaping the child into the most suitable citizen for the country's current society (Opp and Bauer, 2010). Increasing globalisation results in an international competition for high quality education and intellectuals as national assets (Freireiss and Commerell 2019). Furthermore schools, representing a point of congregation and integration, are conceptual entities for cultural, social and intellectual education, as well as physical institutions, providing space for cultivating and developing the urban context.

These educational facilities are the space, where a child is consciously perceiving social experience, responsibilities and possibilities within a society for the first time. This artificial and controlled 'Micro Society' (Schmidt and Schuster 2014) is separated from the exterior space to trial and learn, described as the 'Third space for social interaction' by Opp and Brosch (Opp and Bauer 2014). As early as the 1950s, Reisinger and Schirmer express the need for school buildings to follow the new pedagogical methods, declaring it the 'second home', (1955), verified more than 60 years later by Djahanschah, Auer, and Nagler

(2018). By exceeding the studying space and providing a suitable atmosphere for children, the school ensures the well-being through architecture psychology (Opp and Bauer 2010) and the four qualities of residency, the thermic, hygienic, visual and acoustic (Djahanschah, Auer, and Nagler 2018). In order to maximise the capabilities and progress of the child, an efficient educational infrastructure and a versatile, but appropriate, environment must be introduced. The pedagogue Gerald Hüthers bases this complex ambience on a multifaceted experience, and the confrontation of the familiar and the unknown, stimulating the mental and intellectual growth (Schmidt and Schuster 2014). Opp and Bauer (2010), and Freireiss and Commerell (2019) go even further to declare the 'Room' itself as the entity of the 'Third teacher' by utilising the familiar space, derived from the pedagogical concepts of Reggio. Overall, a school building is a physical institution, which serves as a framework to deliver the entity of a pedagogical concept to increase intellectual development, the social upbringing, and cultural education.

In the introduction of the 'Grundrissfibel' (eng.: Reference work for floor plans) for school buildings Hönig and Nashed state that the actual facilities often outlive pedagogical concepts. Therefore, these buildings must be much more flexible and robust than other typologies (2015). Reisinger and Schirmer strongly agree to design, plan and build schools with the future in mind (1955). Djahanschah, Auer, and Nagler use the concept of 'Kaizen' as the basis for their designs. The Japanese concept suggests that every product or process can be improved (2018), resulting in a constant change of school buildings (Freireiss and Commerell 2019). It does not necessarily call for the demolition and replacement of old facilities, but also maintaining old, functioning buildings, which only need minor renovations because of their long-time acceptance by society and users (Djahanschah, Auer, and Nagler 2018).

Due to these various reasons, such as historical and political context, social and cultural aspects, pedagogical influences, and developments within architecture, the typologies of schools are very complex because of e.g. legal regulations and changing requirements on schools because of e.g. group teaching concepts, instead of frontal teaching by an authority figure. Schools are designed through an interdisciplinary process with careful consideration of all aspects and users of the building, like teachers, students, personel, and the public. In order to categorise and recognise patterns in a case-base, solely essential information is to be extracted from the vast amount of data, meta-information decoded and processed, and its terminology conformed. This school data will be used to generate school variations based on a semi-automatic approach steering a combined system that uses case-based reasoning and deep-learning technologies to analyse and classify facilities according to the external influence, such as history and politics. Further, it is a planning support system for schools to rapidly get new school typologies for constantly changing requirements based on best practice schools.

## RELATED WORK

During the first half of 19th century the facility of a school was an open-plan room within the private home of the village teacher, called 'Einraumschule', where groups of different ages were assigned appropriate tasks (Djahanschah, Auer, and Nagler 2018) (Schmidt and Schuster 2014).

As educational institutes are a political demonstration of cultural and intellectual capabilities (Djahanschah, Auer, and Nagler 2018), in the 19th century schools and educational concepts, such as frontal teaching, were based on military methods. The 'Gangschule' (eng.: Corridor school) was built for optimising this teaching method of large classes, approximately 70 students, which aligned classrooms along one large hallway within a single-depth building (Djahanschah, Auer, and Nagler 2018) (see Figure 1). Around 1900 the teachings of Montessori were introduced, which contained an important component for social learning and assisting the child to learn for itself, still utilising an east-facing 'Gangschule' (Dja-

hanschah, Auer, and Nagler 2018).

Figure 1
Schools in Lichtenberg, Berlin. Schmidt, M. et al., Schulgesellschaft: vom Dazwischen zum Lernraum, Future school buildings, Berlin, Jovis, 2014, p.18.

Especially after 1945, the construction of school buildings rapidly increased (Djahanschah, Auer, and Nagler 2018) and on a political level, German federalism was reintroduced, including that each of the 16 federal states has its own ministry of education. Therefore, the different German states created different school systems and thus, different school building regulations, which are further specified on a communal level. In order to distance themselves from the former pedagogic methods, authoritarian politics and the architectural form language of the 'Gangschule', pavilion schools were introduced (Djahanschah, Auer, and Nagler 2018). Newly constructed buildings, which Reisinger and Schirmer, as employees of the Ministry of Reconstruction of 1955, advocate, emphasize a lot on light, flexibility, expansion, and greenery for playing and movement, but still separate the children by age and gender (1955). They implement these attributes and spaces into the typical 'Gangschule' and finally, advise to use housing technology on a reasonable level (Reisinger and Schirmer 1955).

The schools of the 1960s and 1970s became a space for exchange, equality, information, studies and retreat as the essence of democracy (Schmidt and Schuster 2014) (Djahanschah, Auer and Nagler 2018). Due to the highest number of school enrolment after the Second World War, school buildings became much larger, often called school centres, planned in the manner of a 'Gangschule' as a double-depth building or 'Atriumschule' (eng.: Atrium school), using light-weight construction (Bayerische Fertigbau GmbH 1974). Later it became known that those buildings often led to inferior air quality and even to the 'Sick-building-syndrome', due to fixed glazing and even faulty fully ventilated buildings (Djahanschah, Auer, and Nagler 2018).

The performance of Germany in the PISA ranking in 2000 motivated a reformation of the pedagogical methods and the definite inclusion of pedagogical concepts into school building design was prompted, like Reisinger and Schirmer had already advised 65 years ago (1955). As buildings need to support these concepts, smaller bundled classrooms, separated by flexible walls are arranged around a central common room called 'Marktplatz' (eng.: Marketplace) (see Figure 2). These study clusters or 'Lernlandschaften' (eng.: Study landscapes), derived from the 'Einraumschule' (Djahanschah, Auer, and Nagler 2018), support the dynamic studying of students supporting other students, which stimulates intellectual growth and social skills (Opp and Bauer 2010). Because of these pedagogical concepts, mixed schools of different ages are preferred, as it improves the development of all the children and promotion of talents, and simplifies the transition from one grade into another (Freireiss and Commerell 2019). Further, the future of educational methods suggest team teaching, or co-teaching, of at least two teachers, as well as the student becoming the teacher (Schmidt and Schuster 2014).

Figure 2
First floor of primary school in Karlsfeld by ALN GmbH.

As largely both parents work full-time and students currently remain more hours at school, space for staying, retreat, and supervision is needed in contemporary buildings (Djahanschah, Auer, and Nagler 2018) (Kurz 2015). The circulation area is now used

as additional space or vacant classrooms are repurposed during non-used times (Kurz 2015). Schmidt and Schuster call this the 'In-between space', the physical representation of the pedagogical entity of the school (2014). The contemporary facilities are shaped by limited space, especially in metropolitan areas due to rising student numbers (Freireiss and Commerell 2019) and declining space. Consequently, the area per student has increased. During the 19th century it was about 0.9 $m^2$, between 1945 and 2000 it increased to 2$m^2$ and finally, in the 'Lernlandschaften' 4$m^2$ are provided per child (Djahanschah, Auer, and Nagler 2018). Furthermore, Kurz sees the need for school buildings to open themselves up to the public and offer space as a cultural and social convergence point and for further education for adults (2015). Conveying the notion of a cultural centre amidst a district, schools can also present themselves as a public space, by incorporating service centres, public playgrounds and community centres (Schmidt and Schuster 2014). Furthermore, these buildings can be used as landmarks within areas for orientation and urban planning, due to their form language and positioning (Djahanschah, Auer and Nagler 2018). Therefore, Freireiss and Commerell call the school an 'urban component' (2019).

The experimental 'Open school' in Uto in Japan is a possible future school typology (see Figure 3). L-shaped walls define an open space of a room with nomadic classes, which are changing location for every class. It is supported by the team teaching method and the ability of the rooms to open up the facade and include the exterior as further space in summer.

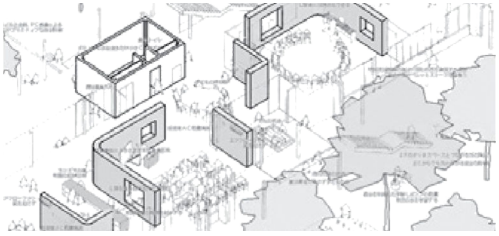


Figure 3
'Open School' in Uto, Japan. Schmidt, M. and Schuster, R., Schulgesellschaft: vom Dazwischen zum Lernraum, Future school buildings, Berlin, Jovis, 2014, p. 93.

## APPROACH

Due to this high amount of factors and requirements, schools include a complex topology and high amount of room types. Even though the design focus of the contemporary twelve schools of 'Future school buildings' (Freireiss and Commerell 2019) is different, the room program is quite similar. These buildings are commonly two storeys high in the countryside, while within the metropolitan area and its resulting lack of space, they tend to be higher, rising up to a maximum of five floors. The different facilities focus on the pedagogical integration of multiple school types with classrooms, study rooms, group rooms, laboratories and space for music, art and theatrical teachings, while providing separate rooms for personnel and teachers, administration, housing technology, storage, meeting rooms, sports facilities, and a large meeting hall, called 'Aula'. A cafeteria, grouped with a kitchen and preparation area, is incorporated, as well as one or more multipurpose rooms, storage spaces, relaxation areas, playgrounds and a function room for events, such as theatrical plays or concerts as a point of congregation for social and cultural interaction through recurring events. Depending on the curriculum, the room program needs to provide specialised spaces like workshops or rooms equipped with advanced technology. The adjoining greenery, an area for playing and movement, is often used as a 'Freiluftklassenzimmer' (eng.: Outdoor classroom) within an assigned space, sometimes with experimental gardens, as well as a public space.

To transform spatial configurations of schools like topological, semantic and geometric information in a computer readable way to serve as a case-base for the generation of variations, using deep-learning, the necessary information is stored in the architectural GraphML (aGraphML) format (Langenhan 2017), derived from the fluent graph format of GraphML, based on the XML format. It is used to depict adjacency, accessibility, depth, flow and analysis of the room program to the user in Rhino3D and Grasshopper3D in a readable visualisation. The Dolphin plugin (Langenhan 2015) for Grasshopper3D, provides a

component to translate into said file format. In the following, the workflow through the different software programs is described, as well as the different steps to convert the extracted information of an Industry Foundation Classes (IFC) file into an aGraphML format to analyse school buildings and generate variations as part of our future work. Furthermore, the results of the variant generation is to be used in Autodesk Revit in later stages.

This workflow offers a software overview, picturing the different programs and plugins, which are currently available, to translate an IFC file format into an aGraphML file format (see Figure 4). For this project REVIT 2020 from Autodesk was used. The plugin Rhino.Inside for REVIT 2020, developed by McNeel, is based on the Rhino3D 7 Work-In-Progress (WIP). It allows extracting and working in real-time with REVIT elements in a separate Rhino window,

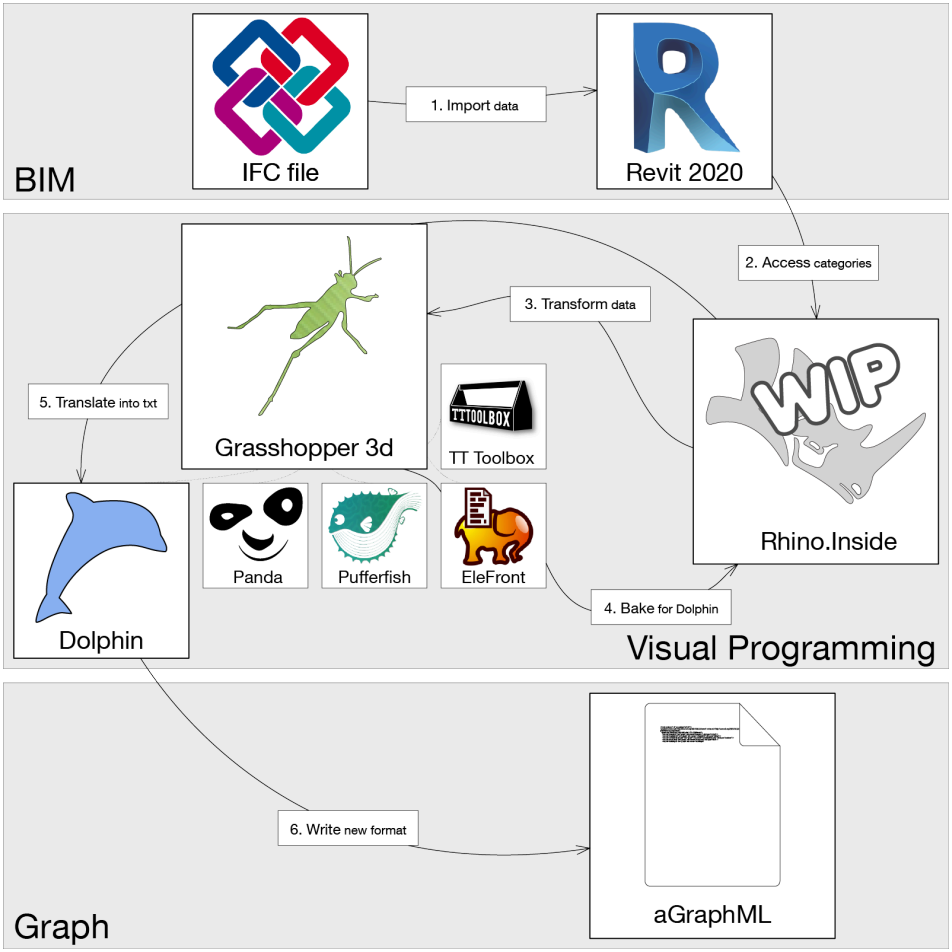
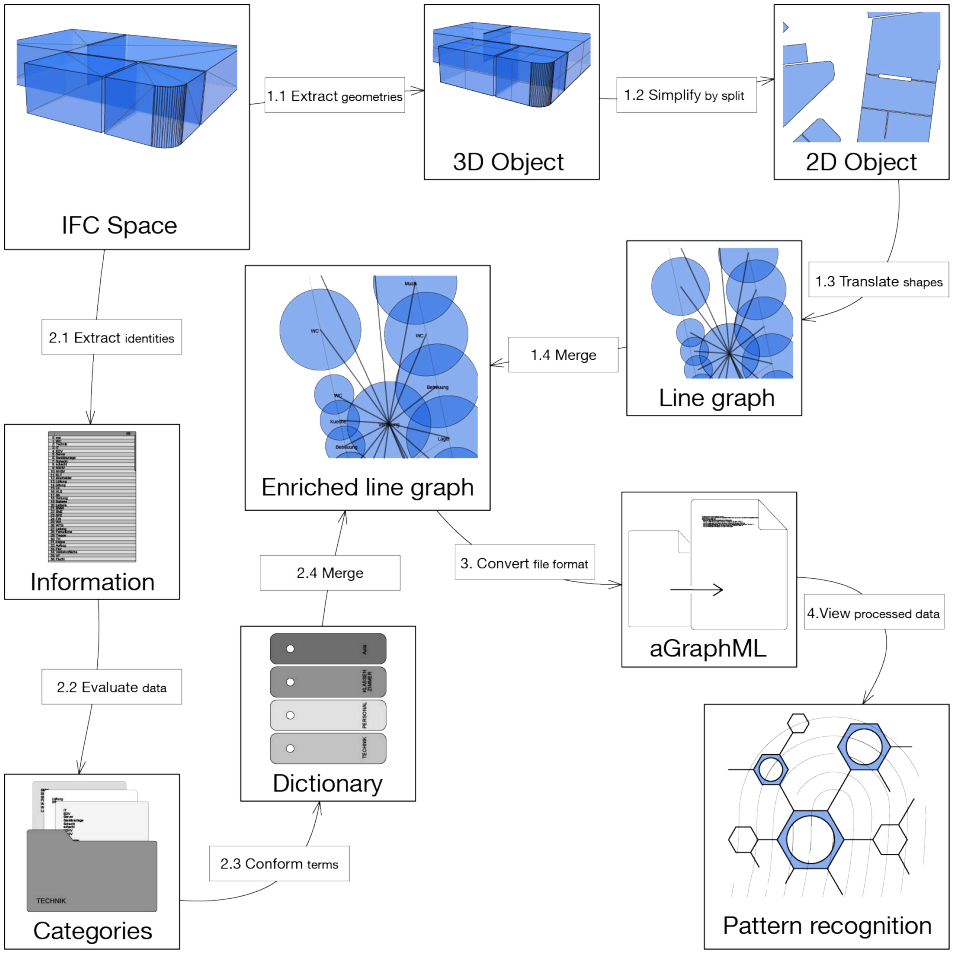



Figure 4
Overview and workflow through software programs.

open in REVIT. Working in Rhino3D offers to work with the parametric design tool Grasshopper for visual programming. Various plugins needed to be installed in Grasshopper, such as Pufferfish, TT Toolbox, Kangaroo2, Panda and EleFront, to transform the available geometries into readable shape language. Further, Rhino.Inside for Revit offers custom components, such as the Category.Picker, Elements.Filter, Category.Identity and Category.Elements. Used correctly, the chosen category elements show as ghosted objects in the Rhino window, as well as the REVIT main window, proving the real-time capabilities of Rhino.Inside. The plugin EleFront is used to assign attributes to the to-be-baked objects. Following, the Grasshopper plugin Dolphin, active in Grasshopper, is able to translate these shapes into the aGraphML format internally. This format then was printed as an XML file into the desired path.

Figure 5
Workflow of steps.



The first work step, as depicted in Figure 5, is extracting the relevant data, using the custom components of Rhino.Inside. The following tasks are simultaneously taken, but apart from each other. In order to create separated storeys as 2D Objects, meshes need to be transformed into Boundary Representations (Breps) and their base surfaces, grouped by the Z value and transformed into circles for readability by the Dolphin plugin. Afterwards, by using the appropriate list for the desired storey level, the chosen objects are isolated. In order to compare different floor plans of schools, the terminology of room names must be aligned. The research on the twelve buildings of 'Future school buildings' (Freireiss and Commerell, 2019) is used as reference to determine a dictionary. The different room names, assigned by different people, organisation, and of different times, must be interpreted by an architect and individually translated. At first the extracted data, represented in a list, needs to be categorised and then conformed under an overlying term. Text-matching is implemented, so keywords or partial words can be used to change the 'Room names' appropriately. Finally, the different categories are baked back into Rhino3D, merging the 2D objects and their conformed semantics, in order for the plugin Dolphin to read and convert it into aGraphML file. As a result a rough topological analysis was performed to identify structural patterns for school building as a basis to develop automatic machine learning approaches. For example, differentiating by names and ranking the sizes, as well as the amount of edges, using Gephi.

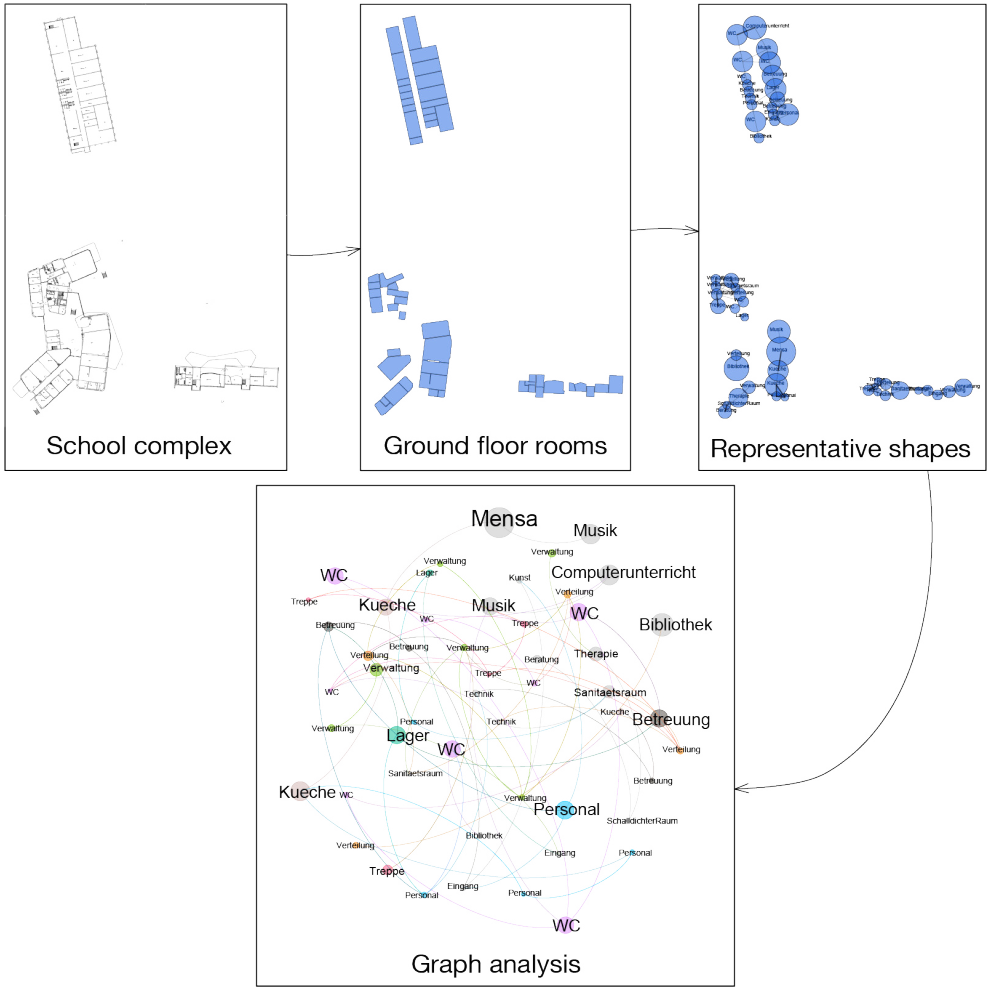
## EVALUATION AND RESULTS

The described workflow and process in Grasshopper has been applied to IFC files of three different school buildings of the architect's office of ALN, Architekturbüro Leinhäupl + Neuber GmbH. Due to the testing with these floor plans, necessary conditions were depicted, improvements in the visual programming have been made, and finally, first pattern recognitions were conducted, using the created visual graph.

The Dolphin plugin has various restrictions, such as the representative room shapes of circles and that the interconnection between two circles cannot be more than one. Further, one circle cannot have more than one room descriptions. During testing, overlays occurred, as the interconnected points and room names are the centre of the circles. Improvements using the available floor plans, led to the development of an automated point correction.

The first tests showed satisfying and encouraging results (see Figure 6). After the automatic point-correction, the aGraphML files can be read, as well as the visual graph is well readable. The first pattern, recognised by the architects, is a correlation between space and size, such as the circulation area, which is very large and often connects or is itself a multipurpose area. As most of the floor plans include study clusters, it becomes clear, that the rooms open to students, are all quite similar in size and shape, but as the children can occupy all of them, the 4m$^2$ per student are achieved. Further, the sequenced succession of rooms, starting at the 'Marktplatz' and ending in the classroom is evolving from a large common room alternating to a classroom through a passage-like small room, called 'inclusions', or a supervision room, which can be accessed from both adjoining classrooms. Gephi revealed that a classroom is linked with at least one other classroom. Group rooms are always connected to at least one 'Unterrichtsraum' (eng.: Teaching room), which is different from the classroom. Simultaneously, group rooms take up about half the area size of a classroom or equally sized 'Unterrichtsraum', thus providing the combined amount of space of 'Unterrichtsraum' and group room during project works, maximising the available square metre per student. Further, the ground floor of school buildings with more than two storeys is used solely for administrative and public rooms, such as library, cafeteria or first aid.

Figure 6
Development
through the
process.




## FUTURE WORK

For further work, the Dolphin plugin is currently being improved. After the first developments, it recognises polygon shapes as rooms, simplifying the entire process of creating 'Wall' and 'Door' line representation and offering the ability to write the actual room edges, simultaneously solving the Boolean edge attribute of 'enclosed room'. Further, a new library for room terminology was created, so the 'Room names' are not converted, but 'Room types' can be recognised by 'Room name' and appropriately written. Finally, an edge representation for windows was created, as well as a Boolean option for 'Windows exist' edge attribute. The latest developments evolve around generic 'Exterior' Nodes and 'Entrance' edge

types. The solution for this includes both improving the Grasshopper components of Dolphin, as well as visual programming using Grasshopper3D.

Finally, after more testing on a larger scale of floor plans, the pre-processed data is to be introduced to an artificial neural network to generate new architectural floor plans, using Deep Generative Modelling. An algorithmic setup issued to build Artificial Neural Networks to generate new data, based on the pre-processed data provided to the model, as suggested in Arora et al. (2020). This data can be used e.g. with a tensor data structure 'relation map', we propose in Eisenstadt et al. (2020) for intelligent variant generation, according to predefined design requirements and finally, an auto-completion of building designs.

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# Drawing Recognition

## *Integrating Machine Learning Systems into Architectural Design Workflows*

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*Machine Learning (ML) has valuable applications that are yet to be proliferated in the AEC industry. Yet, ML offers arguably significant new ways to produce and assist design. However, ML tools are too often out of the reach of designers, severely limiting opportunities to improve the methods by which designers design. To address this and to optimise the practices of designers, the research aims to create a ML tool that can be integrated into architectural design workflows. Thus, this research investigates how ML can be used to universally move BIM data across various design platforms through the development of a convolutional neural network (CNN) for the recognition and labelling of rooms within floor plan images of multi-residential apartments. The effects of this computation and thinking shift will have meaningful impacts on future practices enveloping all major aspects of our built environment from designing, to construction to management.*

**Keywords:** *machine learning, convolutional neural networks, labelling and classification, design recognition*

## INTRODUCTION, CONTEXT, MOTIVATION

If you can understand a floor plan, you can design a floor plan, and to understand you must learn. While this statement might simplify learning one can argue that with Machine Learning (ML), provided enough training, a program can currently become the master of an increased number of things. Popular examples might include strategy such as DeepMind's AlphaGo Zero which, after three days of self-teaching defeated world no.1 Go player Ke Jie [1], or creative endeavours observed in *The Next Rembrandt project*, that generated a new Rembrandt artwork after studying the artist's body of work [2]. Considering the versatility, and rampant accessibility of modern ML algorithms, this research is provoked into exploring ML within architecture, a field with an increasing number of meaningful applied results and attempts (Khean, 2017, 2019).

Yet there is evidence that the Architecture, Engineering and Construction (AEC) industry often resists the integration of modern technologies into their workflows [3]. As outlined by McKinsey in [3] there currently exists a visible reluctance to adopt emerging technologies, which only serves to hinder the means for architects to improve their designs towards more economic, efficient, environmental and aesthetic structures. Consequently these issues drain energy from core design work and compound in a compromised end product resulting in the end users experiencing the built environment negatively and compromising the productivity of the AEC sector [4]. When analysing the productivity gain in other sectors enabled through the introduction of ML [5] (McAfee, Brynjolfsson, 2017) one can clearly argue for the need to introduce ML into the AEC sector as it serves the creation of a nation's critical infrastructure and building stock with currently AU$200B in the pipeline [6] needed to keep pace with the nations population growth [7]. It is an industry crucial to the national economy responsible for 8% of GDP or $134B P.A. [8]. It has, however, been slow to adopt new technology (Deutsch 2019), digitally enabled workflow processes that unlock productivity [4] (Susskind & Susskind 2016; McAfee et al. 2017). We argue therefore for research and investigations into ML's ability to automate *'mundane'* tasks that are essential but not *'very sexy'* in order to increase the productivity of the AEC industry. Items that, amongst others can fall under the category of mundane tasks are compliance checks and the question of how to perform compliance checks (Knodel, Naab, 2016). Specifically, for [NAME WITHHOLD] Architects whom this research was conduct with identified a need to improve solar analysis compliance checking according to the local building code. The code required that only living rooms and balconies needed to be assessed, however the BIM data defining these rooms failed to be transferred from Revit to Rhino. Consequently the [NAME WITHHOLD] Architects questioned if ML could extract relevant information from one place and interpolate it in another.

## RESEARCH AIMS, OBJECTIVES AND OUTCOMES

Accordingly, it is the aim of this research to combat this issue of interoperability and introduce future-proof practices into design workflows through the development of a ML algorithm in the form of a Convolutional Neural Network (CNN) that recognises architectural drawings and is thus able to automatically classify and label elements within floor plans such as individual room properties. It will be the role of the CNN to be given a floor plan as a visual input and output an instance segmentation function on said image, where each room, is classified and the region it occupies is masked (i.e. the pixels inside the region are labelled corresponding to the classification). The CNN accomplishing this aim by automatically producing universal BIM data capable of being delineated across various design platforms. This research additionally contributes knowledge towards architectural understandings of ML, the data created through this research can be extrapolated to assist future machine generation of floor plans.

With this aim in mind the research has the following objectives:

- Despite the nearly ubiquitous presence of ML in research fields and even our popular zeitgeist, there continues to be an underwhelming representation of ML systems within architectural practices. This research's objective is to contribute to how ML can be used in the AEC sector using a pragmatist approach (Gardner et al 2020)
- It appears theoretical developments produced in research scenarios fail to be converted into tools implemented in practical scenarios. The result of this is somewhat of a frustrating situation, where there exists technology that can improve not only the practices but the architecture in which we inhabit, yet it lies dormant and unused. A further objective of this research is using the industry partnership and its applied context as vehicle to identify how practice might use ML.

Considering this context, the outcomes based on the aims and objectives of this research are twofold, to investigate how ML systems can be implemented into architectural design workflows, and if ML systems can develop some form of understanding of design to draw nearer to a goal of machine designed architecture.

Hence as an outcome this research details the development of a CNN that can interpret architectural drawings to classify and label the rooms of residential floor plan images. The CNN can inform the development of an automated room labelling application that can be implemented into architectural design workflows and contribute knowledge to ML understandings.

## RESEARCH QUESTIONS

From these aims, objectives and outcomes the research is provoked into exploring the following key questions:

- *How can convolutional neural networks be utilised within AEC design workflows to optimise or automate the recognition, classification and extraction of architectural elements such as rooms?*
- *How can machine learning algorithms synthesise the elements, topologies, values, etc. of floor plans to identify, distinguish and separate between the spaces within?*
- *To what extent can machine learning algorithms understand and interpolate architectural design? And to what extent of sophistication must a ML algorithm have to generate design?*

## METHODOLOGY

This project adopts the design action research methodology to inform and guide the course of work undertaken. Action design research as proposed by Maung K. Sein (2011), is an approach whereby the generation of knowledge is motivated by the discovery of problem situations in a specific organisational setting and through an iterative cycle produces an evaluated *'IT'* artifact that addresses said problem. Likewise, this research is motivated by present issues observed within AEC design workflows (through the research partnership with [NAME WITHHOLD] Architects, and through the construction of a ML algorithm produces knowledge which will be used to inform an *'IT'* artifact that will automate, and thus solve/alleviate the issue. Following the structure of action design research this research is divided into three separate stages which operate in this manner: investigate, act, observe.

In the first stage (problem formulation), architectural design workflows are observed and investigated and after exploring ML a specific problem is formulated and the strategy by which to solve it. In the second stage (building intervention and evaluation), the Neural Network (NN) is constructed and the accuracy of its predictions and the robustness of the system is assessed, since this is an iterative approach this step may repeated a number of times before a satisfactory result is attained. Finally, in the third stage (reflection and learning), moves thinking into a conceptual frame where the knowledge, applications and implications obtained from producing the NN is ascertained.

## BACKGROUND RESEARCH AND LITERATURE REVIEW

ML is by no means a recent technology, examples of applied ML can be traced back to Arthur Samuel's checker player for the IBM 701 in 1952 (Barto, Sutton, 1992). However, today with access to unprecedented computational powers and open source tools such as TensorFlow and PyTorch have enabled us to openly explore ML outside of traditional computer science fields. Mario Carpo (2017) predicts that the effects of this computational shift will see design informed by the mass retrieval of data and information, an environment where ML technologies may thrive and potentially create a new form of artificial intelligence. Certain types of ML enables a program to perform given tasks without explicit instruction through a process of training. Tom M. Mitchel of Carnegie Mellon University (1997) states that *"A program is said*

*to learn from experience with respect to some class of tasks, and performance measure, if its performance at tasks, as measured by performance measure, improves with experience."*

A particular field of ML comes under the umbrella of deep learning, commonly associated with the implementation of artificial neural network (NN) architectures. NNs probe mass quantities of data to find statistical correlations, patterns, trends etc. and extract this metadata to inform an output such as some form of prediction, classification or suggestion. As their name suggests NN draw loose inspiration from biological models of neural networks like the brain, a NN is a series of interconnected neurons that receive, affect and send data [9]. The process by which a NN learns is surprisingly brute force by nature, using forward and backpropagation and NN receives an input and is told to produce an output, the data it is fed has labels associated with it (supervised learning) that inform the NN of the desired (correct) outputs. The NN iteratively receives a piece of training data, produces and output, finds out its wrong, fine tunes itself, repeats, and now is slightly less wrong. The is a process referred to as gradient decent and can be likened to climbing down a mountain blindfolded, and after a long enough cycle the NN has a series of values and hyperparameters that consistently produce (mostly) correct outputs when it receives a certain class of input data.

Of particular interest are prior mentioned Convolutional Neural Networks (CNN), they possess the ability to extract patterns from spatial data types and are thus frequently used in image recognition tasks. With accurate training methods a CNN architecture have achieved high accuracy rates in image classification tasks (Hinton, et al, 2017). CNNs operate in two stages, firstly they detect features by applying convolutional operations over images on a pixel level, and secondly, they classify features in later layers by developing understandings of detected features. But what is the current state of play in the AEC industry?

There currently exists only a handful but growing number of research examples that explore the capacity of ML system to be applied to architectural endeavours, leaving many questions concerning the legitimacy of ML in this field open. To provide a few examples; Ng (2018) employed CNNs to distinguish between sections and plans (Ng, 2018). Chaillou's (2019) AI + Architecture demonstrates ML's ability to classify, validate and generate architectural drawings. Yoshimura, Cai, Wang & Ratti's (2018) research suggests that ML can comprehend design to the extent that researchers from MIT managed to differentiate designs between architects using a NN [10].

Through the literature review in the above, specific research findings were discovered that helped inform the course of this research. In one case Huang, Zheng (2018) used a generative adversarial network for the recognition and generation of floor plan images, and achieving interesting results. However, the decision to generate a training dataset from a single data source (that being marketing floor plans from a Chinese website) resulted in an overfitted NN which was unable to correctly classify non-orthogonal plans or plans that did not pertain to the specific design style the NN was trained on, thus rendering itself useless in all other situations. This example highlights the importance of the data to determine the success of ML applications.

Ferrando et al. (2019) investigated the CNNs ability to distinguish between building typologies of monasteries and mosques, training their CNN on floor plans of these typologies. Again, it was the process of data collection and pre-processing that proved most crucial and laborious/time consuming. This research proved to be quite insular in its final application in practice as it concentrated on monasteries and mosques whilst training of the CNN was, in most respects successful.

Equipped with these insights, the research team started its collaboration with [NAME WITH HOLD] Architects with the aim to investigate ML technology towards the architecturally oriented goal of recognising architectural drawings and thus being able to automatically classify and label elements within floor plans such as individual room properties.

## CASE STUDY

The existing research above demonstrates that ML can be used to classify architectural topologies, assess designs through a certain metric such as compliance regulations, make predictions and assessments on projects or even directly influence design decisions. But this research project specifically aims to explore drawing recognition and classification of spatial types in multi-scale residential floor plans to inform the development of an automated room labelling workflow for use on residential architecture projects. The project was divided into four key stages that involved ML processes research, data collection and processing, script development, testing, reflection and the production of a ML floor plan recognition model.

### *Researching Machine Learning and existing applications in the AEC industry.*

The first stage of the project involved researching machine learning and existing applications in the AEC industry. In combination with the above listed literature review these findings informed the appropriate ML methodology to adopt, the requirements of this methodology and the feasibility to perform all requirements to contribute new findings. This stage necessitate the creation of a CNN, trains it on labelled floor plan images, and generate a program that takes its predications and produce classification instance segmentation labels. When completed successfully and all components work harmoniously with each other one has produced a ML algorithm whose outputs will inform an automated room labelling workflow and ML understandings towards design.

Research specific to this stage concludes that using the Python programming language with the open source ML library TensorFlow and the Keras API in the Visual Studio Code IDE is the optimal approach to create the CNN. This step is based on existence of the extensive documentation, learning resources, compatible tools and community support provided by users of these popular tools. Consequently it enables a higher chance of successfully producing an optimal CNN that will accurately perform its desired task. The development of a CNN can be synthesised into three main components: (a) assembling layers, (b) compiling model and (c) fitting model. The process of ML in CNNs has previously been delineated in the background research section of this paper, therefore the paper will describe these three components in detail.

Assembling layers defines the structure of the CNN; the number of layers and the purpose they have (whether they perform a convolutional or pooling operation for instance), the number of neurons and their activations (Sigmoid, Relu, Softmax, etc.) and, what amount of potential outputs it can produce (size of the output layer). Essentially, one defines how data is fed into the CNN, interpreted and converted into an output. Compiling the model defines the ML metrics for the processes of learning in forward and back propagation, the loss and optimiser functions that are used to analyse the performance of the CNN during training, and inform how the weights and biases are altered to improve output accuracy. Fitting the model segments the dataset into training, and validating and giving them to the CNN, the training set is the largest (approximately 90% of the images) and is used to inform the learning. The images are accompanied by labels which are the image's desired outputs if it were to be fed to the CNN. Within the training cycle the CNN wants to produces outputs that match these labels to the greatest degree of accuracy possible. The validation dataset are used almost as a test; it withholds a small section (˜10%) of the data to show after training to assess the model's performance and ensure that the CNN has not been overfitted with the training data (when the CNN is too closely trained on the specific examples in the training data and thus becomes useless in any practical scenario).

### *Gathering floor plan images, labelling images and pre-processing images into a dataset to feed the CNN*

The second stage involved gathering floor plan images, labelling images and pre-processing images into a dataset to feed the CNN to enable training to commence. Typically, ML algorithms require massive quantities of varied data which posed a problem to this research in collecting enough to form a substantial dataset to enable any meaningful ML developments. Initially it was thought that marketing floor plans could easily be sourced from real-estate companies, this proved false. Fortunately, [NAME WITH HOLD] Architects provided a dataset of 454 floor plan images from their previous projects. These consisted of CAD drawings, marketing images, and hand-drawn floor plans from a variety of multi-scale residential buildings. Despite, still the limited size of this dataset, it was believed that quality of this data would make up for this limitation, furthermore, the feasibility of manually labelling 454 images within the span of this research made it quickly apparent that whether the dataset size was satisfactory or not was of lesser importance to the feasibility of compiling and processing data.

As argued earlier, ML is mostly about the data. Consequently this stage of the project proofed to be by far the most extensive and time consuming. This is logical, ML is entirely dependent on the data it is provided to learn, if there exists flaws within this data the ML product is made redundant. The supervised learning approach employed by this research required all the images collected to be accompanied by a label in the form of a .JSON file that defined the regions in which certain room classes were occupying. To simplify this task and focus the efforts of the ML algorithm, it was decided to make six room classes for the CNN to search for, these being:

- Bedroom
- Bathroom (includes ensuite)
- Living room
- Dining room (if connected to the living room, counted as part of the living room)
- Kitchen
- Balcony (includes terraces, patios, etc.)

The images were labelled using the VGG image annotator (Dutta, Zisserman, 2019), this involved drawing the regions that rooms occupied and defining said region as whatever room it was. The output of this process was a large .JSON file that contained every label for all the images and would be referenced for the training cycle.

### *Develop program that could perform instance segmentation on test data*

The third stage involved developing a program that could perform instance segmentation on test data. Instance segmentation is the classification of multiple class regions within a single image and produce a mask that defines the space the classes occupy within the image. This task proved itself to be too computational advanced for this research to build from the ground up. Consequently the Mask R-CNN framework developed by the Facebook AI Research Group was employed [11]. Using the pre-defined functions from Mask R-CNN and altering them to fit our data and project's desired outcomes within our own scripts enabled us to create a CNN capable of meeting the aims of this research. With a CNN, a dataset and a framework for instance segmentation, training commenced over a period of 1000 epochs. Initial training cycles failed due to various memory and iterative errors, after a process of debugging and re-writing to more efficiently pass data (alleviating the stresses on the system), a full training cycle was completed. The finalised CNN model was then exported as a .h5 file containing the finalised hyperparameters to an inference script where testing was conducted.

### *Testing and evaluation of the CNN*

The fourth and final stage involved the testing and evaluation of the CNN. With a completed CNN running instance segmentation on floor plan images, new test images were inputted. Overall the results were satisfactory and demonstrated that CNN was

beginning to develop a fundamental understanding of design. The test images were purposely varied in design typologies, visual style, and size, they even included floor plans from projects outside of Australia and plans where features such as furnishing were absent, through this the CNN was validated as tool of wide capabilities. The CNN began with randomised values and through the training cycle developed its own methods to detect and interpret floor plans. Through testing it is evident that a multitude of factors informs its decision-making processes these are: (1) visual features including symbols, icons, line work, patterns, etc and (2) the shape and form of elements within the image and relational data, for instance the layout of floors and general design principals that dictate how we design the spaces we inhabit. The ability for the CNN to rely on multiple features is good because it means it makes it a more robust system capable of dealing with more floor plans that may be unique in their features and styles. However, the CNN is far from perfect, it is evident that from viewing its outputs that there is yet to a be a single *'perfect'* output where rooms are labelled exactly and correctly, these issues will be further discussed in the next section of this paper.

## DISCUSSION, EVALUATION AND SIGNIFICANCE

The aim of this research was to develop a ML algorithm that could understand designs of floor plans and subsequently be used to inform the creation of an automated room labelling application. This research documented the development of the CNN for this purpose, it has shown an initial success in reading and labelling architectural drawings, that with further refinement and training with additional data will be a sophisticated, reliable tool. Hence the research was able to demonstrate how ML systems and thinking may be applied and integrated into architectural design workflows to optimise practices within design workflows.

CNNs do possess the ability to understand and interpret design within an architectural framework if directed and trained correctly. A CNN possesses an elementary ability to classify rooms and an advanced ability to distinguish between spaces. Due to only being able to train the CNN with a dataset of 454 floor plan images we believe that the results with additional training data sets will improve. The CNN initially randomises the variables by which it detects features and only through trial and error during training discovers what is of significance to complete its task successfully. From analysing several of the CNNs outputs it is evident that a number of factors informs its predictions. These factors include features such as the addition of text, symbols and icons (e.g. the word bedroom and a bed symbol), line work such as room boundaries (walls) and patterns (floors), and most interesting to this research, relational data. It is possible that the CNN is unintentionally learning design rules and compliances through its brute force training approach to learning, such as room sizes (e.g. the largest room is the living room), room layout (e.g. the balcony is separated from the rest of the floor plan, often accessible only through another room) and room shapes (e.g. the bedrooms often have wardrobes which extrude out from their otherwise thick rectangular typology).

To elaborate on this point further. In an example for instance, the CNN may find that bathrooms typically contain a number of visually distinct graphics (e.g. the symbol for a toilet, shower, bath and sink) within a narrow much smaller space in relation to the rest of the floor plan, confined by thick lines and chequered pattern within the bounds of said lines and contextually close to bedroom regions. So, when the CNN is viewing an image containing a bathroom/s it may rely on some or all these things and potentially more to formulate a bathroom prediction. There are, however, aspects that continue to confound the CNN's prediction making process, larger images with too many class instances appear to overwhelm the program, this however may just be a limitation of the hardware (standard university lap-

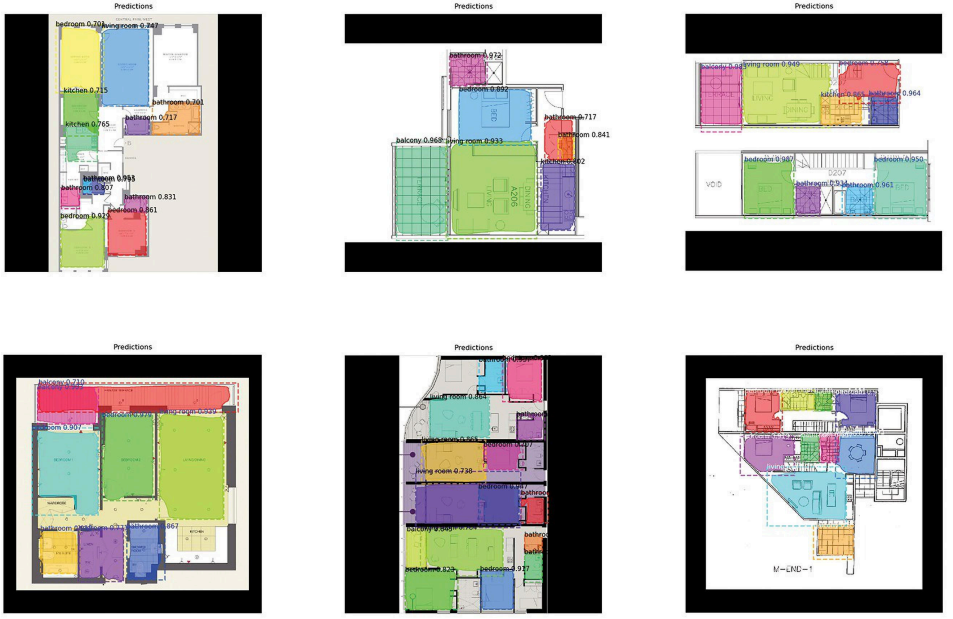


Figure 1
Various Room Labelling Results

top - Microsoft Surface Pro) available to this research. More serious issues pertain to aspects of classifying and distinguishing. Popular trends in modern design facilitate open space living, thus blurring the separation between the kitchen, living room, and dining room. In many tests cases the CNN's distinction between between rooms connected in open space living were unsatisfactory, and often displayed an uncertainty. Rooms that are visually similar on floor plans such as a laundry and bathroom occasionally result in incorrect classifications. With more extensive training these nuanced problems can be overcome. Furthermore, it is clear that these problems are not fundamental issues within CNN's but are a result of research limitations.

A further point of contention comes from the selection of training data. Here the issue of data size (454 floor plan images) is an obvious one, ideally the size of the dataset would have been in the thousands. Despite this limitation, this research has already proven that within this limited dataset a CNN can understand design. Consequently a larger dataset would simply make it more sophisticated. However, a more important, less visible limitation was data variety availability, this research used exclusively floor plans that [WITH HOLD] Architects designed. This is significant because it may mean that the CNN is learning the biases and design preferences of [WITH HOLD] Architects, resulting in a layer of subjectivity in a tool that is desired to be objective. Another fear sparked by this revelation is that of overfitting the CNN, where the data is too specialized to a specific context, that being [WITH HOLD] Architects's work that the CNN fails to be a universal tool that other firms can benefit from. It is unclear whether simply brute forcing this issue with more

training data will overcome these concerns and is a more philosophical question that will be investigated with further inquiry beyond this research.

## CONCLUSION

Currently we stand at a crucial time for architecture (Deutsch, 2019) [12] [13], the decisions made by firms now, will dictate their prosperity for the next decade. It is clear that it is a necessity for the AEC sector to adapt and open up to emerging technologies. Proponents of technology have identified a lack of automation and adoption of technology as the primary reasons for the AEC industry's poor performance (Chapman 2005; Deutsch 2019; Khean et al. 2019). We argue amongst others that the AEC industry needs reform if it is to sustain and grow in the new economy (Brynjolfsson et al. 2014; Susskind, Susskind 2015; McAfee 2017; Parker et al. 2016, van Rijmenam 2019). Automation technologies have the potential to help AEC firms sustain or even grow as they experience inevitable digital transformation. That is why investing in further ML investigations and applications in architecture is of significance, the knowledge collated in this research has proved that even with a several limitations a CNN can be produced to optimise, automate and improve several processes that previously hindered design workflows.

This research is definitely preliminary, addressing the statement made in the introduction alluding to floor plans designed by machines and the technology produced by this research is not capable of such a feet, the level to which the CNN understands design is yet to surpass or even attain to a human's cognitive ability. In the spectrum of design oriented applications, however, initial applications where the ML algorithms work in tandem with architects to suggest and inform design decisions are within reach. The applications that can be produced as a direct consequence are quite staggering, the results of this research possess a multitude of direct and indirect implications. Directly, we know that an application where floor plans are read and automatically labelled can be produced after another, more in depth training cycle and indirectly we can see that ML opens the door to the concept of automatically generated, universal data, where this thinking can be applied to a plethora of other scenarios.

With further developments of ML in architecture, and if we divulge more of our data and general architectural information to ML algorithms, then the concept of a Synthetic Design method combining ML with computational design for an optimised design workflow consumable for humans via a web-browser in and for Architecture, Engineering and Construction (AEC) disciplines becomes feasible (Haeusler, 2019). The effects of this kind of computation shift will be staggering, ML will divulge information concerning design that humans are cognitively incapable of perceiving, informing better, optimised and automated design practices. The consequence of this computational shift will ultimately augment the perceptions we as designers have towards our built environment and the means by which we conceptualise, design and create it.

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# Architectural Visualisation with Conditional Generative Adversarial Networks (cGAN).

## *What machines read in architectural sketches.*

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*As a form of visual reasoning, sketching is a human cognitive activity instrumental to architectural design. In the process of sketching, abstract sketches invoke new mental imageries and subsequently lead to new sketches. This iterative transformation is repeated until the final design emerges. Artificial Intelligence and Deep Neural Networks have been developed to imitate human cognitive processes. Amongst these networks, the Conditional Generative Adversarial Network (cGAN) has been developed for image-to-image translation and is able to generate realistic images from abstract sketches. To mimic the cyclic process of abstracting and imaging in architectural concept design, a Cyclic-cGAN that consists of two cGANs is proposed in this paper. The first cGAN transforms sketches to images, while the second from images to sketches. The training of the Cyclic-cGAN is presented and its performance illustrated by using two sketches from well-known architects, and two from architecture students. The results show that the proposed Cyclic-cGAN can emulate architects' mode of visual reasoning through sketching. This novel approach of utilising deep neural networks may open the door for further development of Artificial Intelligence in assisting architects in conceptual design.*

**Keywords:** *visual cognition, design computation, machine learning, artificial intelligence*

## INTRODUCTION

While computer aided design tools are ubiquitously used in architectural practice, design ideation and conceptual design have long been dominated by hand sketching.(Goldschmidt 1994, Simon 1996) The development of a mental model and its transformation into a symbolic construct, and (self-) communication through visual output seems to be directly linked to manual visual activity, namely sketching. During early design stage, architects and designers often communicate their ideas through visual imagery such as sketches, whether to enter a self-dialogue or to communicate ideas with an external audience. Goldschmidt (1994) is convinced that "[n]o

sophisticated tools such as the computer era provides us with can bypass creative visual thinking." A fundamental characteristic of these early conceptual sketches is their ambiguity. Forbus (2012) argues that improvements in the ability of computers to understand human conceptual and ambiguous imagery will subsequently unlock a revolutionary way for architects and designers to share their concepts and ideas with computers through the intuitive means of hand sketches. The deciphering of ambiguity is a cognitive process of higher order. Higher-order cognition allows humans to accumulate knowledge and understand abstract concepts from sketches. Further, higher-order cognitive activities, such as functional, conceptual and visual reasoning are instrumental in creative problem solving in the field of design and invention. Therefore, for computers to have any important role in creative problem solving, artificial intelligence and machine learning algorithms must be able to perform higher-order cognition. This will enable them to 'understand' and 'interpret' abstract sketches, such that they can be utilised in the algorithmic creative processes.

When architects think via sketching during the design process, they produce series of sketches, from which they see and reflect until new ideas emerge. An important and key question that follows is how machine learning can contribute in such form of visual reasoning. In this paper, a novel machine learning algorithm is proposed to imitate this cyclic process.

## SCOPE OF RESEARCH

Artificial intelligence (AI), also known as cognitive simulation or information processing psychology, is developed on computers to simulate how human beings think and work. There are two main goals of AI research. The first one is to make computers smarter, so that they can take over mundane tasks from us, and the second, to help us to understand our tasks better so that we can improve the way we work (Simon, 1983).

Deep learning is an emerging sub-branch of machine learning in AI, which is capable of learning higher-order features, and is therefore useful in developing methods to understand and imitate the sketching process in architectural design. Amongst the generative algorithms in deep learning, the Conditional Generative Adversarial Network (cGAN) has shown to be highly adaptable and applicable in a variety of image-to-image translation applications (Mirza and Osindero, 2014), and is therefore most suitable for developing the method in simulating architects' visual reasoning process of abstracting and imaging proposed in this paper.

As discussed earlier, architects produce sketches and revised them repeatedly from the preceding ones during the early design stage. A new machine learning algorithm is developed here to imitate this cyclic process based on the cGAN. For convenience, this novel deep learning algorithm is denoted by Cyclic-cGAN in this paper. The training of Cyclic-cGAN will be presented and its performance demonstrated with hand sketches.

## RELATED WORK

### *Sketching as a Mean of Reasoning*

Drawings and imageries have been means of human communication for a long time. Although drawing may be considered primitive in comparison to language, it is an intuitive form of communication and recording. Creating imageries from experience, memory or ideas is a crucial part of human cognition. An understanding emerges through the repeated morphism between imagination and representation, where a mental model transvers into a symbolic construct and vice versa. Through morphism, the embodied structure of the mental model turns into a symbolic structure, establishing a meaning - symbolic form pair. (Belcher, 2020). Conceptualisation trough a meaning - form pair is not bound to a specific medium of symbolic form. The symbolic form would include characters and symbols, word or language, objects and drawings.

While communication through language is bound to grammar and a mutually agreed set of symbols, to generate a meaningful semantic visual representation is "...unbounded by convention, imagery tolerates idiosyncrasy in thought and supports novel forms of synthesis (Kaufmann, 1980)". Note that visual representations, in two or three-dimensions, made for the purpose of communication (with clients, colleagues or other interested parties) or to facilitate evaluation, is not what we mean by visual thinking. It is the production of ideas, the process of reasoning that gives rise to ideas and helps bring about the creation of form in design (as opposed to its rendering) that is of interest here (Goldschmidt, 1994). The lack of conventions and the unrestricted grades of abstractness are the reasons why architects tend to rely on external representations, in forms of sketches and diagrams, to assist the design process. These external representations are not merely memory aid, but a form of visual or spatial reasoning, in search for design solutions.

Problem solutions, particularly design solutions, emerges through the repeated morphism between mental models and symbolic representations. Sketching is the manifestation of such an iterative cyclic process, during which a design solution is developed. (Schon and Wiggins, 1992; Goldschmidt, 1994; Suwa and Tversky, 1997). The process of inspecting and reacting to the preceding sketches repeatedly is a "conversational structure of seeing-moving-seeing" (Schon and Wiggins, 1992). From this cyclic process of sketching, new and innovative ideas are born, where there is a desirable ambiguity and mutual influence of idea and form. "A concept may lead to a figure just as a figure might lead to a concept" (Goldschmidt, 1994).

When an architect thinks via sketching, she produces a series of sketches, which she observes and reflects upon until new ideas emerge. Architects often keep their sketches vague and symbolic to maintain a fluid exchange of figural and conceptual arguments. There seems to be a direct link between the process of sketching and the generation of mental images. "When sketching an imagined space, or an object being designed, the hand is in a direct and delicate collaboration and interplay with mental imagery. The image arises simultaneously with an internal mental image and the sketch mediated by the hand" (Pallasmaa, 2009). However, this connection seems to be intrinsic to the sketcher and thinker but inaccessible to out standers.

### *Deep Neural Networks*

Amongst the machine learning algorithms, Deep Neural Networks (DNN) are capable of learning and generating higher-order features (Dang and Yu, 2014; Schmidhuber, 2015). The Generative Adversarial Network (GAN) is a deep learning network that consists of an adversarial pair of DNNs, the generator and the discriminator (Goodfellow et al. 2014). The objective of the generator is to generate novelty images that can deceive the discriminator. In contrast, the objective of the discriminator is to become better in identifying that the training images are real, but the generated images are fake. The structure of GAN enables it to learn high-order features, as the discriminator learns from a given training set, while the generator learns from the feedback of the discriminator. After learning, the generator can then generate images that are convincing enough to 'fool' the discriminator in believing the generated images are real.

The cGAN (Mirza and Osindero, 2014) is derived from GAN. While the GAN generates novelty images $z$ from random noises $z$, the conditional GAN (cGAN) generates novelty image $x|z$ from random noise $z$ with training data consisting of an conditional image pairs $x|y$ with the goal of generating an novelty image while retaining the image structure of input $x$.

To improve the performance of GAN, the cGAN is derived by adding an input, denoted by $x$, to the training set, such that the images generated by cGAN will retain the image structure of $x$ (Mirza and Osindero, 2014). It is shown that with the addition of $x$, cGAN is highly adaptable and applicable in a variety of image-to-image translation applications (Isola et al. 2018).

However, with the added input $x$, the generator of cGAN tends to generate blurry images in the presence of uncertainty. To overcome this shortcoming, pix2pix cGAN is developed by adding an additional term to the loss function in the training algorithm that increases the penalty when the image generated by the generator deviates too much from the input $x$ (Isola et al. 2018). This aims to restrict the discriminator to concentrate only on the higher order features but allowing the lower-order structural correctness to be handled by the generator. Further, a new discriminator architecture that penalises structure at the scale of patches is proposed, which is referred to as the PatchGAN (Isola et al. 2018), which is a form of texture loss for identifying whether a $N$ x $N$ patch in an image is real or fake. With this modification, the performance of pix2pix cGAN is better than cGAN, and has been successfully applied to a range of applications in recognizing higher-order features, such as the label-to-image from photographs of building facades (Isola et al. 2018), and producing artistic painting from some arbitrary images (Akten, 2017). Consequently, pix2pix cGan or simply pix2pix will be used to develop the machine learning algorithm in this paper to imitate the cyclic sketching process in the early design process.

## METHODOLOGY

As discussed previously, cGAN (Mirza and Osindero, 2014), is capable of learning and generating higher order features, it is therefore selected in this paper to develop a machine learning algorithm that imitates the cyclic process of abstracting (sketches) and imaging (images) in the early architectural design process. This cyclic process of visual reasoning essentially involves two steps: one to transform sketches into images, and the other, from images back to sketches. The proposed machine learning algorithm, Cyclic-cGAN, therefore consists of two cGANs, one for each step. After designing the structure of the Cyclic-cGAN, the training procedure of the Cyclic-cGAN is then developed.

The data set, which consists of 84 sketch-image pairs, are prepared by selecting 84 images of small and medium sized buildings, with sketches produced by tracing each of these images manually. The Cyclic-cGAN will be trained with 80 of the training data, each consists of the image and its respective sketch. The trained network will then be tested using the remaining 4 sketch-image pairs. To illustrate the performance of the Cyclic-cGAN in visual reasoning, 4 black and white sketches are used, 2 of which are drawn by experienced architect, and the other 2 by architecture students. Details are presented in the following sections.

## CYCLIC CONDITIONAL GENERATIVE ADVERSARIAL NETWORK (CYCLIC-CGAN)

Sketching as a mean of visual reasoning is a non-static process. Seeing and moving are equally important during the development of a design concept. Architects often produce series of sketches to expand on the preceding ones, or to redraw them in a different way. Sketching is therefore a repetitive process, and each individual sketch contributes to the overall transformation. Much like a frame in time, the order of each individual sketch has its role within the sequence and the overall transformation.

"The drawing that appears on the paper, the visual image recorded in my cerebral memory, and a muscular memory of the act of drawing itself. All three images are not mere momentary snapshots, as they are recordings of a temporal process of successive perception, measuring, perception, evaluation, and re-evaluation" (Pallasmaa, 2009)

The understanding of a sketch is complete, only if it is viewed in conjunction with those preceding and succeeding it. The constant exchange of abstraction and imagery facilitates transformation. New ideas subsequently emerge from such cyclic process.

In contrast to the other generative networks, the condition introduced in cGAN restricts the output to retain the structure of the input image, which can be in the form of colour label, sketch, photograph or images of objects. Instead of generating images arbitrarily as in GAN and its variations, this feature

gives cGAN additional control on what it can generate. Therefore, cGAN is more likely to produce images that architects find relevant, hence more useful to their work.

The conditional input incorporated in cGAN enables it to see something as something else, which is the essence of imagery. Although this is a significant advancement in machine learning, nearly all applications of cGAN are for generating an output for a given input, simply as a translation tool. Sketching is a mode of thinking and spatial reasoning performed by architects (see Figure 1), which is a cyclic process. Architects interact with their sketches, in search of visuals clues that may spark a new way of seeing the sketches that could eventually lead to new ideas. In this paper, a machine learning algorithm to imitate such cyclic process based on cGAN is proposed. To generate an alternative view of the sketch produced by architects, another cGAN, or the inverse cGAN, is used to generate a sketch from the image generated by the first cGAN. The sketch generated by the inverse cGAN can be considered as an interpretation, or another way to view the original sketch, as it is produced from the image generated from the original sketch. This reconstructed sketch subsequently becomes the input to the first cGAN to generate another image, and the process is repeated. The sequences of results generated by this cyclic process would show how the original sketch is gradually transformed.

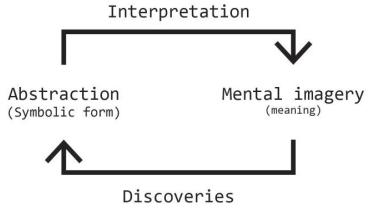



Figure 1
The cyclic process of visual reasoning

This pair of cGANs will be referred to as the Cyclic-cGAN. Although it is implemented through pix2pix, the same approach can equally be applied to other implementations of cGAN.

### *Workflow of Cyclic-cGAN*

The Cyclic-cGAN illustrated in Figure 2 consists of a pair of cGAN (pix2pix) trained with the same training set. The first cGAN is trained to translate sketches into images (imaging), while the second cGAN trains to convert images into sketches (abstracting). As the second one performs the inverse translation of the first one, i.e. the input of the first one becomes the output of the second one and vice versa. The first cGAN performs the usual translation function of the cGAN by generating image from sketches, while the inverse cGAN reconstructs the sketch from the image produced by the first one. Consequently, the original sketch will be transformed through this cyclic process. In this way, the Cyclic-cGAN simulates the cycling process of abstracting and imaging in visual reasoning.

**Cyclic-cGAN Workflow.**

1. Prepare and select the training data.
2. Train the first cGAN with sketches as the input and images as the output.
3. Train the inverse cGAN with images as the input and sketches as the output using the same data training set as in 2.
4. In the first iteration, the trained first cGAN is used to generate an image from a novel sketch prepared by the architect.
5. With the output image of the first cGAN, the trained inverse cGAN is used to generate a sketch
6. The generated sketch becomes the input for the first cGAN to generate another image
7. Repeat Stage 5 and 6 until the halt condition is satisfied (ie. a relatively defined from emerged).

Through the repetition of imaging and abstracting, the Cyclic-cGAN would be able to pick up some visual clues that are "meaningful" to it and transform the input sketch based on its knowledge.

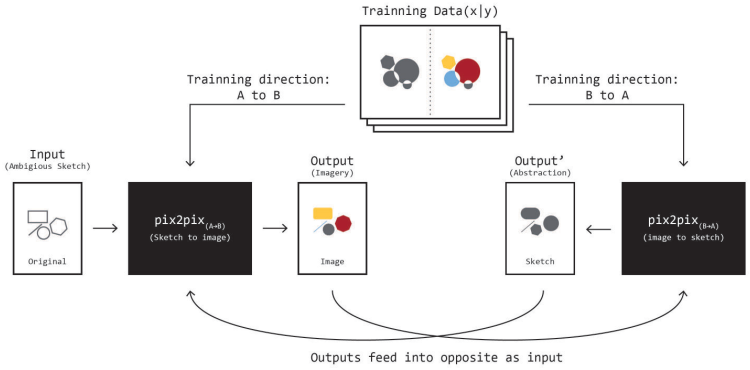



Figure 2
Diagrammatic representation of cyclic-cGAN

### *Implementation of the Cyclic-cGAN*

The training of cGAN for the experiments described in this paper is based on TensorFlow implementation of pix2pix (Hesse 2017).

**Hardware.**

- Processor Intel® Core(TM) i7-6700 CPU @ 3.40CHz 3.41 GHz
- RAM 16.0GB
- System type 64-bit Operating System, 64-based processor
- GPU NVIDA GeForce GTX 970 with 4Gb memory

The training of Cyclic-cGAN follows the workflow described previously. The training set is prepared by the following procedure:

**Data Preparation Procedure.**

1. Collect sketches and images of the buildings, which will be stored in two separate folders, one for sketches and the other for images.
2. Create two folders, **A** for sketches and **B** for images.
3. Resize sketches and images in both folders into 256 x 256 pixels:
4. Pair the corresponding images and sketches using the processing tool provided by the software provider using the following command, as illustrated in Figure 3:
5. Split the combined images into training and testing data using the processing tool provided by the software provider.

Figure 3
Merging training data

After the training set has been prepared, the combined image/sketch pairs will be randomly allocated into the training data set and stored in the folder, **train**, and the validation data set in **val**. The two cGANs in the Cyclic-cGAN are then trained using the folder **train**. The first cGAN will be trained with the sketch A as input to the image B as output while the inverse cGAN will be trained in the inverse direction with the image B as the input and the sketch A as the output, as shown in Figure 4.

Figure 4
Illustration of inverse training direction of the Cyclic-cGAN

**Training Procedure for both cGAN.**

1. Set up a folder for the checkpoint of the first cGAN: A to B.
2. Initiate the training of the first cGAN.
3. Set up another folder for the checkpoint of the inverse cGAN: B to A.
4. Initiate the training of inverse cGAN.
5. The image size was restricted to 256x256px and the number of training iterations (max_epochs) to 200 to keep computing time reasonable.

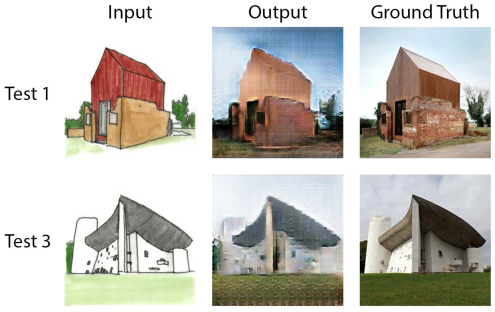
### *The Training Set*

To train the Cyclic cGAN in the experiment, 84 images of small to medium sized buildings are selected. They are chosen as these 2 classes of buildings tend to contain less context in contrast to larger buildings that often include wider cityscapes. Subsequently, this allows the cyclic-cGANs to focus solely on the buildings. The sketches of each image are produced manually by tracing from their respective images and colour coding are also used to identify different materials. Two examples of these training data are shown in Figure 5, while the full set of 84 sketch-image pairs can be found in Chan (2020).

Figure 5
Examples of training data

From the 84 sketch-image pairs, 80 are assigned to the training set and the remaining 4, the validation set for testing the performance of cGAN in generating images from the sketches. Figure 6 shows the performance of the trained cGAN by comparing the input sketch, ground truth and the image generated by the algorithm.

Figure 6
Results from the sketch-image translation cGAN in the Cyclic-cGAN




## INTERPRETIVE PERFORMANCE OF CYCLIC-CGAN

### *The Experiment*

As discussed previously, to enable discoveries and transformation, the input sketch should be foreign and ambiguous to the Cyclic-cGAN, as arbitrary shapes contain 'clues that can be isolated, possibly combined, and deciphered as reminiscent of something that is meaningful in a particular context' (Goldschmidt, 1994). For this reason, black & white line drawings are used as input to the Cyclic-cGAN. Four input sketches are considered here, as shown in Figure 7. Sketch 1 is by Alvaro Siza (Guerra and Romano Santos, 2020) and sketch 2 by Frank Gehry (Archiscape, 2020). The other two (sketch 3 and 4) are drawn by two different architecture students with the instruction to sketch an imaginary building.

**Experiment Procedure.**

1. Prepare a selection of input sketches and pair them with blank images using the data preparation procedure. Place the sketches in the input folder 1, **in1**.

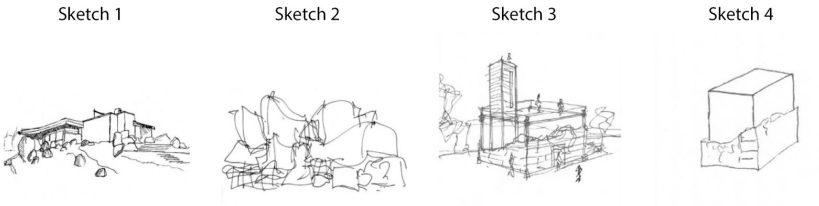



Figure 7
Black & white input sketches for the experiment

2. Create the output folder, **out1**. Use the first cGAN to generate images from **in1**.
3. Create new folder for input, **in2**. Copy the input and output from **out1** and place them in separate sub-folders **A** and **B** inside **in2**. Always locate the sketch in **A** and the image in **B** regardless of direction.
4. Create the output folder, **out2**. Use the second cGAN to generate sketches from the images in **in2**.
5. Rename the files in both **A** and **B** such that the sketches are matched with their corresponding images. Combine the two with the processing tool, as described in Step 5 of the Data Preparation Procedure.
6. Create new folders for input, **in3**. Copy the input and output from **out2** and place them in separate sub-folders **A** and **B** inside **in3**. Always locate the sketch in **A** and the image in **B** regardless of direction.
7. Rename the files in both **A** and **B** such that the sketches are matched with their corresponding images. Combine the two with the processing tool, as described in Step 5 of the Data Preparation Procedure.
8. Repeat steps 2 to 7 until the Cyclic-cGAN eventually generates definitive shapes.

### *Discussion of Results*

As illustrated in Figure 8, the Cyclic-cGAN appeared to be searching for clues during the initial phase of iteration and to formulate an understanding of the input sketches. In the first iteration, the Cyclic-cGAN generates images that demonstrates its initial understanding of the input sketches. The first generated image resembles the general shape and form of the original sketch, though lacking in distinctly defined edges. Due to the ambiguity of the first imagery, some features of the input sketch are either distorted or omitted in the sketches generated in subsequent iterations, resulting in a change of spatial relations and subsequently leading to new discoveries. These discoveries gave rise to new meaning, and through further rumination of imaging and abstracting, the Cyclic-cGAN concluded with a more definitive shape. The iterative and cyclic process within the Cyclic-cGAN has gradually refined features in the sketches, turning an ambiguous architectural sketch into a realistic representation of an architecture, and hence illustrates its performance in visual reasoning.

More specifically, the dominant features of the input sketches shown in Figure 8, as would be interpreted by architects, are highlighted in red dashed lines. The dashed lines illustrate the similarities between human interpretation and the recognition of these features by the Cyclic-cGAN. It is also observed that the Cyclic-cGAN can identify skies and surroundings, although no such feature is articulated in the sketches. Furthermore, materiality in form of colour is assigned to certain elements by the Cyclic-cGAN, again with little articulation in the sketches. Continuities in colour and form, foreground and backgrounds seem to manifest during subsequent iterations, illustrating again its visual interpretation capability.

Figure 8
Results generated by Cyclic-cGAN with 80 training data

## CONCLUSION

Since the pix2pix, derived from cGAN, has shown to be capable of visual interpretation, it is chosen in this paper to develop the proposed Cyclic-cGAN. The iterations in the Cyclic-cGAN is comparable to architects' cyclic cognitive process of imaging, interpreting and abstracting. This process can be interpreted as a Hegelian dialectic, with imagery being the thesis, and abstraction, the antithesis

From the results of the experiment, the proposed Cyclic-cGAN is able to transform the input sketches to images. In the first iteration, the Cyclic-cGAN interprets the input sketch by isolating, removing and regrouping features in the input sketch. New spatial relations are subsequently formed through the iterations of Cyclic-cGAN, and consequently the original sketch is transformed based on these newfound relations. Cyclic-cGAN's ability in interpreting ambiguous sketches through this iterative process could potentially assist architects in visual reasoning. By removing or highlighting sketched features, Cyclic-cGAN could encourage architects to find new meanings in their sketches. Further, Cyclic-cGAN could generating images that might provoke architects into seeing their previous sketches in a different perspective.

Computers have so far provided little assistance to architects in conceptual design, specifically in the process of visual reasoning. With the Cyclic-cGAN we propose a step towards the goal of utilising computers to assist architects in design ideation.

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# An Exploratory Urban Analysis via Big Data Approach: Eindhoven Case

## *Measuring popularity based on POIs, accessibility and perceptual quality parameters*

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*The cities are equipped with the data as a result of the individuals' sharings and application usage. This significant amount of data has the potential to reveal relations and support user-centric decision making. The focus of the research is to examine the relational factors of the neighborhoods' popularity by implementing a big data approach to contribute to the problem of urban areas' degradation. This paper presents an exploratory urban analysis for Eindhoven at the neighborhood level by considering variables of popularity: density and diversity of points of interest (POI), accessibility, and perceptual qualities. The multi-sourced data are composed of geotagged photos, the location and types of POIs, travel time data, and survey data. These different datasets are evaluated using BBN (Bayesian Belief Network) to understand the relationships between the parameters. The results showed a positive and relatively high connection between popularity - population change, accessibility by walk - density of POIs, and the feeling of safety - social cohesion. For further studies, this approach can contribute to the decision-making process in urban development, specifically in real estate and tourism development decisions to evaluate the land prices or the hot-spot touristic places.*

**Keywords:** *big data approach, neighborhood analysis, popularity, point of interest (POI), accessibility, perceptual quality*

## INTRODUCTION

This paper presents an exploratory urban analysis for Eindhoven to understand the urban vitality of the city. Jacobs (1961) defines urban vitality as "a measure of positive activity or energy in a neighborhood that makes an urban place enjoyable to its residents." Public space is vital if there are various activities and uses for people (Jacobs 1961), where the place is easy

to access to activities for all (Montgomery 1998), and the perception of life quality is satisfactory (Jacobs 1961). The public spaces face the risk of degradation due to the lack of vibrancy in modern cities. Measuring urban vitality becomes crucial to make decisions in regenerating the public spaces. However, urban vitality is an abstract, complex, and multidimensional concept challenging to measure.

The research utilizes popularity as a measure of urban vitality. The project approaches the degradation problems in two ways, by analyzing values associated with popularity, and their connection, which affects the probability of a neighborhood being popular. The focus of the research is to investigate the interdependencies between POIs, accessibility, and perceptual quality factors and their impact on popularity in the city. The objective of this research is to present an alternative method to measure the city's vitality. The main research question addresses that to what extent the factors of urban vitality increase the probability of a neighborhood being popular.

The research implements a big data approach for data collection to measure the variables. The city is equipped with information networks that lead to a significant volume of data with big volume and variety. A big data approach is the analysis of different datasets to create knowledge or reveal hidden relations. The big data approach enriches our understanding of how the city dynamics and community pattern function and provide more informed decision-making for liveable public places (Batty 2013). The generation of big user data changes the data collection method. User-generated content (UGC) is the data shared by users about their activities, perceptions, and interactions using information and communication technologies (ICT) through smart mobile applications. While users make sharings from social platforms, they share the location where the information created, the time when taken, and the content of the sharings.

While other conventional data gathering methods are time, labor, and cost-intensive and reflect a static snapshot of the urban environment, UGC presents a time-efficient method for data collection to capture the city's dynamics (Zhou and Zhang 2016). However, this method has limitations due to data bias (Cranshaw et al. 2011), accuracy, and privacy issues within the difficulties in ICT literacy in the public, known as the digital divide. This research combines conventional data surveying with user-generated data (UGD) analysis regarding their challenges. It employs multiple data sources to measure each variable; web scraping of UGD for popularity and accessibility, aggregate data for POIs, and survey data for perceptual quality.

This paper is structured as follows: it starts with the introduction of the research topic, follows a literature review and the research methodology, and concludes with the results, discussion, and further directions.

## LITERATURE REVIEW ABOUT VARIABLES

The literature review mentions the state of art researches to explore how to measure the variables and understand their level of interdependencies. The research will measure the level of popularity, based on the density and diversity of POIs, the accessibility and perceptual quality to gain insight into the vitality of the city. Therefore, the literature review elaborates on the variables -which are (i) popularity, (ii) point of interest (POI), (iii) mobility, and (iv) perceptual quality.

### *POPULARITY*

The social network data has been widely used to identify attractive places and their popularity level. The location-based social-networking data (check-ins from Foursquare) is employed to understand human travel flows and identify the city venues, where accommodates widely used POIs (Sun et al. 2016). Ensari and Kobas (2018) utilize Instagram data to find out which places are popular based on the Instagram posts, a count of likes, and the content of comments about the places through the web scraping method.

Alivand and Hochmair (2017) define the photo-sharing platforms as abundant resources of crowd-

sourced spatial data. The photo-sharing platforms (Panoramio and Flickr) are widely utilized for spatiotemporal analysis to identify attractive places (Kisilevich et al. 2013), rank the popularity of places (Schlieder and Matyas 2009), and map the visitor movement and density pattern (Girardin et al. 2008). This project opts to employ Flickr photos to determine the popularity of the neighborhoods, regarding the conducted studies, using the Flickr platform [1].

### *POINT OF INTEREST (POI)*

Points of interests (POIs) indicate places where human activities take place and which attract people to visit somewhere like restaurants, shops, museums, universities, or parks (Gao, Janowicz, and Couclelis 2017). Jacobs (1961) points out that the presence of dense POIs and their balanced combination with different functions make neighborhoods live all day long. Besides, Gehl (2010) describes POIs as a side effect of people going to an area due to its exciting mix of attractive places is that people attract more people in a self-reinforcing loop. Thus, the presence of POIs is considered a factor that is extremely related to this project's primary research question.

According to Yue et al. (2017), the association between the mix of POIs and high popularity needs more study because some neighborhoods planned with the intention of 'mixed-use' still lack popularity and hence to what degree mixed-use can influence popularity is worthy of further investigation. In this study, the diversity and density of POIs diversity per neighborhood are extracted to evaluate the point of interest. The first is to study the theory that a good use mix promotes popularity, and the later, to understand the extent to which the level of mix-use and concentration of POIs affect popularity.

### *ACCESSIBILITY*

Accessibility is an essential characteristic of livable urban spaces making a space more attractive. Accessibility refers to people's ability to reach goods, services, and activities, with a transportation mode. Appleyard, Gerson, and Lintell (1981) emphasize the liveability of the streets by investigating the accessibility opportunities, physical conditions (traffic, noise, pollution), social interactions, and perceptions of the street. Tan (2016) indicates that accessibility and environmental quality have a significant influence on neighborhood satisfaction. Saghapour and Moridpour (2019) point out the positive impact of neighborhood accessibility -in particular the public transport and walkability- on inhabitants' decisions to select their neighborhood. Based on the literature, it can be deduced that more accessibility in urban spaces provides more opportunity for activities, improves neighborhood satisfaction, and consequently increases the probability of being popular.

There is a growing interest in research studies examining the relationship between accessibility and the neighborhood's liveliness. The big travel data, including crowdsourced travel data, social media data, and navigation data, offers new possibilities for data collection methods. In the literature, Google Distance Matrix API has been employed as crowdsourcing travel data for understanding the relationship of accessibility with traffic (Moya-Gomez et al. 2018), and evaluating in traffic flow estimation (Wang and Xu 2011). This study employs Google Distance Matrix API [2] for collecting travel time and distance data to evaluate the accessibility of the neighborhoods.

### *PERCEPTUAL QUALITY*

The perceptual quality indicates the satisfaction level of the neighborhoods, and the satisfaction level influences neighborhoods' popularity level to visit and live. The study takes into account the safety, population, and social interaction related factors to understand the perceptual quality of the neighborhoods, regarding the literature research. Among these criteria, the safety level -the perceived safety and crime rate- acts the most determining role in neighborhood satisfaction. According to Baba and Austin's (1989) study, neighborhoods with higher levels of satisfaction tend to have a higher perception of safety. The crime rate sets the essential criterion in the literature to analyze neighborhood satisfaction (Newman and Duncan 1979). The correla-

tion between population characteristics and residential satisfaction stems from a sense of place (Speare 1974), the duration of occupation, and social interaction among residents (Galster 1987). While the residents' occupancy duration has a positive impact (Hur and Morrow-Jones 2008) on residential satisfaction, the ethnic diversity influences social interaction negatively, consequently on residential satisfaction (Galster 1987; Speare 1974). Lastly, social interaction plays a vital role in the community (Sirgy and Cornwell 2002). The research accounts for the social cohesion level, the residents' leisure activity level, and their participation rate in activities.

Regarding the literature review, we utilize geolocated Flickr photo counts to measure the level of popularity, the density and diversity level of POIs to the attractiveness, travel time-distance values with different means to measure the accessibility, and safety, population and social interaction related factors to measure the perceptual quality level for each neighborhood. The study establishes a conceptual model to analyze these variables, as displayed in Figure 1. The research measures the popularity level according to the level of attractivity (POI), accessibility, and perceptual quality in Eindhoven's neighborhoods.

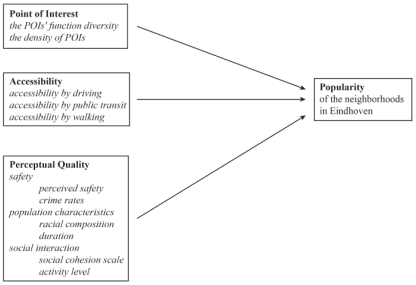


Figure 1
The conceptual model of the project

## METHODOLOGY

The project's methodology follows three phases to conduct the exploratory analysis: data collection, data visualization, and data analysis. The researchers conduct web-scraping for geospatial data and crowdsourcing travel data and employ statistical and spatial aggregate data from relevant institutions to gather quantitative data about variables. In data visualization, the researchers map these different quantitative datasets to obtain spatial information. In data analysis, the researchers conduct a Bayesian Belief Network (BBN) analysis to identify the probability of the relationships between each variable.

For popularity variables, the study employs geolocation data of Flickr photos to create the spatio-temporal database of users to find the popular place in Eindhoven. Flickr geotagged photos present spatial, temporal, and textual information (e.g., location, time, tags, twitter description). The Flickr Platform has higher accessibility via its developed Application Programming Interface (API) in comparison to other UGC platforms, and reliable georeferences with its GPS coordinate data. Flickr presents an API for developers free in the Flickr App Garden platform [1]. This platform presents variable APIs for extracting metadata of the photos. We select Flickr due to its feature of being reliable, accessible, and rich content extraction via its APIs. The data collection method is web-scraping through the Flickr API ('flickr.photos.search') to evaluate the popularity of a neighborhood. We enter the bounding box longitude and latitude values of each neighborhood as an input, and the API gives the total number of photos, with its user id, taken time, and title.

For the POI variable, the research employs BAG (Basic Registration of Addresses and Buildings) dataset, which opens to public use by municipalities of the Netherlands [3]. The BAG dataset stores precise information about the status of the buildings, its surface area, geometry, location coordinates, year of construction, and purpose of use. The research utilizes the BAG dataset to obtain information about the number of buildings within their functions in Eindhoven. The POIs are classified per neighborhood and

function. The diversity and density of POIs are calculated for each neighborhood using this classified dataset. The total number of POIs provided by the Central Agency of Statistics [4] dataset was divided by the total area of the neighborhood for the POI density.

Regarding the studies in the literature (Yue et al. 2017; Hao et al. 2014), the research implements Hill numbers method to calculate the density and diversity of the POIs. The Hill numbers method is commonly used as a unified form of diversity measurement in ecological literature that includes richness, entropy, and the Simpson index adapted to measure the diversity level of POIs, regarding Yue et al. (2017). The general formula of the Hill number is given by (Yue et al. 2017):

$$D^q = \left( \sum_{i=1}^{s} p_i^q \right)^{\frac{1}{1-q}} \quad (1)$$

In Equation 1, Di denotes POIs diversity, S the number of functions, pi the relative abundance of its functions, and q denotes the parameter that indicates the sensitivity to the relative abundances, when it is equal to zero, what this formula measure is the POIs' function richness (Hao et al. 2014). They (Yue et al. 2017) evaluated that when the q values are equal to zero, the function richness has the strongest association with the neighborhood popularity. Therefore, in this project, the function richness formula is used to compare the POIs diversity level in different neighborhoods. For the POI density, the total number of each POIs was divided by each neighborhood's total area, which is indicated in the CBS data table, as shown in Equation 2:

$$De = N_p / A_t \quad (2)$$

This study employs Google Distance Matrix API [2] for collecting travel time-distance data and Eindhoven in Figures Data Platform [4] for the population data in each neighborhood while evaluating the accessibility. We extract the number of the user from Flickr and tabularize by coding in Python as a solution to missing data in several neighborhoods. Based on the data analysis, the visitor population is included in the missing districts, and the ones that have more visitors than the resident population are updated. For calculating the travel time, we assume the location of Eindhoven Station as the origin and the center of the neighborhoods of Eindhoven as destinations. We calculate the travel distance and travel time value for travel modes (public transportation, driving, and walking) from the origin to each destination. To obtain the travel time value for each O-D set, we scrap the travel time and distance value for each destination from Google Matrix API using the programming tool, Microsoft Visual Studio. We take Feng and Zhang's (2014) evaluation as a reference to measure the zone level accessibility. We calculate the accessibility index of each neighborhood using Equation 3. In this study, the accessibility index (Ak) is calculated through the function of the zonal population (Pj) and interzonal travel time (tk), while the capacity of enhancement (yi) and interzonal travel impedance parameter (θ) is accepted as the neutral element.

$$A_k(y_i| \in I_I) = \sum_{j \neq k} \left[ \frac{P_j}{t_k} (y_i | i \in I_I)^{\theta} \right], \forall k, j \in N \quad (3)$$

To evaluate the perceptual quality, we utilize Eindhoven in Figures platform, which is open to public use by Eindhoven Municipality [4]. This platform presents residential, economic, social, and safety databases in the neighborhood, district, or city-scale [4]. Regarding the literature, the selected databases are perceived safety and crime rates for safety, racial composition and duration for population characteristics, social cohesion, and activity percentage of the habitants for social interaction, regarding the literature review. The missing values in some databases arise from the lack of respondents in the survey, as Eindhoven Municipality indicates through the interview by e-mail.

For the data visualization stage, we import unstructured datasets of variables to the GIS platform. We classify the variables data according to the grading system (very high, high, moderate, low, and very low) and map these quantities using the equal inter-

vals classification method in the QGIS tool. The spatial analysis demonstrates which district accommodates a higher level of the variables and what is the general pattern of the city. The comprehensive evaluation of the spatial analyses gives valuable information about the association between the variables, which will be discussed in the result section.

Finally, we utilize Bayesian Belief Network (BBN) to analyze the interdependency relationship between the variables. BBN is a reasoning tool for decision-making under uncertainty (Cheng et al. 2002). BBN utilizes the probabilistic reasoning method to correlate the variables based on the probability of the connections between the variables (Smith et al. 2018). Smith et al. (2018) indicate that BBN is useful for an explorative design context, the methodology of the study. In this study, the Bayesian network analysis helps understand the extent to which the variables influence the popularity of the neighborhood, which is the research question of the study. The study employs GeNie software, a graphical user interface (GUI) of SMILE Engine, and allows for interactive model building and learning [5]. We classify the aggregated datasets according to the grading system with equal intervals. Then, we construct a BBN network by using the variables' datasets as input and selecting the proper learning algorithm. The learning algorithm used was the Greedy Thick Thinning, which adds and removes arrows to connect the variables until a maximum marginal likelihood is achieved [5]. The system constructs a network learning based on the background knowledge from the input data. We optimize the background knowledge by forbidding the improper relations and relating the discrete parameters according to the inferences from the literature review. BBN network results show a positive and relatively high connection between popularity, level of population change, accessibility by walk, and density of POIs. The detailed results of the BBN network will be discussed in the result section.

## RESULTS

Performing a spatial association between the variables, which are popularity, POIs' density and function richness, accessibility by public transit, driving and walking, and perceptual qualities, and their correspondent neighborhood resulted in the maps in Figure 2.

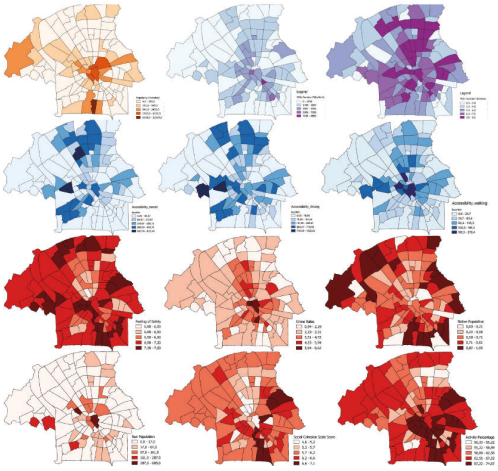

Figure 2
The maps of geospatial analysis for each variable

Most of the neighborhoods can be considered as not popular since they do not have enough photo counts. The neighborhoods from the first three categories are mainly residential areas; therefore, it is expected that they have a lower popularity level. The ones in the second category are differentiated from the ones in the first category since they are near to the more popular neighborhoods. The fourth category, which is in the second order in terms of popularity, has four neighborhoods around the city center as expected. One of them is TU Terrein, where the university campus is, due to its location and type of users. The most popular neighborhood, Sportpark Aalsterweg, surprisingly came up. There is a sports center organizing several events during the year since there are too many photos in this neighborhood.

The POIs' function richness and density follow a similar distribution, being generally the more dense areas, also the ones with more functional diversity. While a small number of neighborhoods concentrate the majority of the POIs, the number of functions is more spread throughout the city, resulting in that even areas with medium to low densities have a certain number of functions available.

The accessibility by public transportation, driving, and walking value follow a similar distribution, in particular, the accessibility by driving and transit values have more similarities. The travel time from Station to the neighborhoods ranges between 5-35 minutes by car, between 5-100 minutes by transit and between 11-400 minutes by walking. In the central zone, the travel time changes between 10-30 minutes, however, the population is an indicator factor; the places with fewer respondents (Tue Terrein) have lower accessibility index despite shorter travel time. For instance, the areas (such as Prinsejagt, Het Ven, Genderbeemd, t Hool), further from the center, have the highest accessibility index, due to the highest resident population. The areas in the central zone (Binnenstad, Philipsdoorp, Villapark, and Schrijversbuurt) have higher accessibility due to the high population and shorter travel time. When overlapping the popularity and accessibility maps, in residential areas with a higher density such as Binnnenstad, Villapark and Irisbuurt have both high accessibility and popularity due to short travel time and high population. However, in lower-density residential areas, Tue Terrein, Fellenoord, Stirjp-S have higher popularity but lower accessibility due to the low population despite shorter travel time.

The feeling of safety is seen as similarly distributed between the neighborhoods in contrast to the crime rates. The crime rates have reached the highest values in Looiakkers, Witte Dame, and Binnenstad neighborhoods. However, these neighborhoods are distributed in the fifth and fourth categories of feeling safety. Therefore, it can be claimed that there is no relationship between how people perceive safety and crime rates. The native population map shows us that the percentage of native people is higher than 58% in 79% of the neighborhoods. According to the literature review, this should be a good result in terms of racial homogeneity of the neighborhood. When we look at the run population, in 69% of the neighborhoods, the population does not change significantly, which is decent for the residents' satisfaction level. Lastly, the neighborhoods with very high participation in activities also include neighborhoods with very high social cohesion scores.

### *Bayesian Belief Network Analysis Results*

After performing spatial analysis for each variable, the BBN network was structured to reveal the relations between them and displayed in Figure 3. Besides the relations, it is also possible to see the relative strength of the associations using a Euclidean method by the average. The strongest associations were found between the popularity - change in the population, the walking accessibility - POIs density, and the feeling of safety - social cohesion in the neighborhood. The states are organized as very low, low, medium, high, and very high.

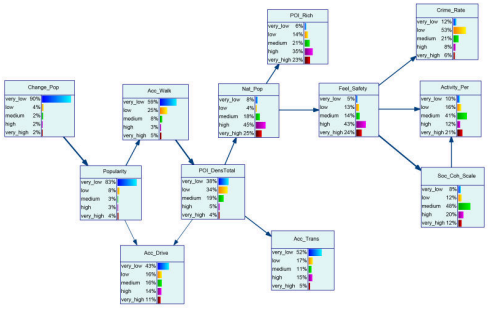


Figure 3
The network result of BBN analysis

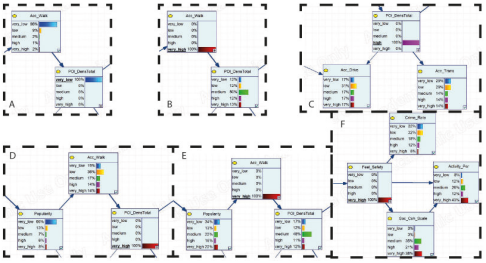

Figure 4
A: Effect of a very low POIs density on accessibility by walk B: Effect of very high accessibility by walking on POIs density C: Effect of a high POIs ' density on accessibility by car and public transport D: Effect of a high POIs ' density on popularity E: Effect of very high walk accessibility on popularity F: Effect of a high feeling of safety in other social factors

Regarding the POIs variables, POIs density had a close relationship with the accessibility variables. The direct effect of walk accessibility on POI's density resulted in 86% of the chances of a neighborhood having very low walkability when a very low density is considered. When very high walkability is considered, the chances of them being of at least a medium density is 75%.

Beyond these direct connections, an indirect effect of POIs density in POIs' function richness and feeling of safety was observed through the native population variable. None of the POIs variables were directly associated with popularity. However, while POIs function richness had barely any effect on it, POIs density had a better response with a high density generating a drop from 83% of probability of a neighborhood having very low popularity to a 68% probability and a very high density being associated to a 66% probability of a very low popularity rate.

Regarding the accessibility variables, popularity affects accessibility. The probability of being highly popular (100%) decreases the probability of not being accessible from 59% to 17% by walking and from 40% to 19% by driving. It shows that popular places would have more easily accessible options by foot or driving, or accessible places have more probability of becoming popular. The accessibility by walk is closely related to popularity with a 0.24 strength connection. The probability of high walk accessibility (100%) increases the probability of very high popularity from 4% to 22%.

Regarding perceptual quality variables, an only change in population had a close relationship with popularity. The relationship seems strong and direct. According to the literature study, we were expecting more relationships between the perceptual qualities and popularity; however, from the BBN network, it can be said that the change of the perceptual variables does not affect popularity. The network between the feeling of safety, crime rates, activity percentage, and social cohesion score makes sense in terms of interconnectivity. A very high feeling of safety leads to an increase in the probability of a lower crime rate, more social homogeneity, and more active residents in the neighborhoods.

## LIMITATIONS

This research encounters some limitations concerned with the different types of datasets. The analysis of popularity is limited with the Flickr users, and Flickr data since the popularity of neighborhoods is measured with Flickr's geo-position data. The use of social media is a valuable source of data for urban research, in particular, Flickr was used by several surveys that also looked for confirmation of its effectiveness through other sources as interviews with the population (Cranshaw et al. 2011) and cell phone networks (Girardin et al. 2008) with positive results. However, it has limitations such as data bias, the accuracy level, and population group due to the nature of social network data.

The limit in data samples in social network data might cause data bias towards the place and people's age group, as the references indicate it for all types of geospatial social data (Cranshaw et al. 2011; Sun et al. 2016). The people tend to share the attraction points more to get more likes and comments than their location or experience in that location, causing bias in place. Moreover, the demographic distribution of social media platform sharings is part of the young population, which uses smartphones and applications widely, and this is cause to bias in age group (Cranshaw et al. 2011). Another limitation is related to the private user accounts in the Flickr platform. The API neglects the result in data analysis, which would cause the loss of information about that user's photos. Since several attractive places have private ac-

counts, their photos were not taken into account during the photo analysis. In the further stages, the popularity analysis can be supported with other georeferenced data such as check-ins, the crowdsourcing mapping applications (Tripadvisor and Yelp), and tweets or comments to overcome the challenges and gain a better understanding about the attraction points.

In terms of accessibility, the measurement of accessibility is limited with travel time and neighborhood population. For instance, the mobility to several neighborhoods is difficult, but their accessibility indexes are satisfactory (above the very low level) due to the population, such as Riel. In contrast, some neighborhoods have easy mobility, but they have lower accessibility index due to less population, such as Tue Terrain. For this reason, the accessibility measurements might be expanded by considering other travel parameters such as travel cost, impedance, or distance to get a better understanding of the accessibility in further stages.

Even with these limitations, this research was able to extract useful conclusions from the Flickr data set. In Eindhoven, popular neighborhoods have a dynamic social profile and a high density of places, and they are walkable. Thus, an urban plan that enhances these characteristics in stagnated neighborhoods has a better probability of increasing the livability in these areas. This study opts to employ different datasets rather than multiple geosocial data regarding the limitations of using UGC platforms. The formal datasets taken from the relative institutions present more accurate information in terms of population features and the condition of the built environment. The study assumes that the use of UGC can be complemented with other data types to obtain more valuable information.

## CONCLUSION

The project's results partially agreed with the literature research with a high level of walking accessibility and POIs density associated with a high probability of popularity. In this sense, the results presented here support the contemporary urbanism trend of more compact cities that active incentive transportation. Additionally, neighborhoods, where the social composition is renovated every year in this city, are more popular than areas with a stable population. This result points to social dynamics as a relevant feature of popular and liveable areas.

For future research, the researchers recommend further investigation of the POIs diversity since the data set utilized here was not enough to capture the richness of functions in a more elaborated level. Moreover, social factors should be expanded to include the perspective of the neighborhoods' visitors. In terms of accessibility, the researchers offer to employ more travel-related parameters to examine neighborhood accessibility. Finally, in terms of popularity data analysis, the researchers recommend enriching the data analysis with another social data network and complementing it with surveys.

Regarding the outcomes of the analysis, this exploratory research can extract useful conclusions. This approach might contribute to the field of urban informatics, and also has the potential to be used in real estate to evaluate the land price according to its popularity and in tourism to identify the hotspot places within its relational factors. The relations found in this exploratory research can be useful for policy-makers in decision-making about urban development, considering liveability to prevent degradation in urban areas.

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# A big data evaluation of urban street walkability using deep learning and environmental sensors

## *a case study around Osaka University Suita campus*

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*Although it is widely known that the walkability of urban street plays a vital role in promoting street quality and public health, there is still no consensus on how to measure it quantitatively and comprehensively. Recent emerging deep learning and sensor network has revealed the possibility to overcome the previous limit, thus bringing forward a research paradigm shift. Taking this advantage, this study explores a new approach for urban street walkability measurement. In the experimental study, we capture Street View Picture, traffic flow data, and environmental sensor data covering streets within Osaka University and conduct both physical and perceived walkability evaluation. The result indicates that the street walkability of the campus is significantly higher than that of municipal, and the streets close to large service facilities have better walkability, while others receive lower scores. The difference between physical and perceived walkability indicates the feasibility and limitation of the auto-calculation method.*

**Keywords:** *walkability, WalkScore, deep learning, Street view picture, environmental sensor*

## INTRODUCTION

Walking is the most basic green transportation mode which plays an irreplaceable role in the integrated transportation system. Streets, as the main carrier of walking and the valuable urban public space, are highlighted for their various value. Walking-friendly streets can improve the life quality of residents and enhance their physical fitness. Walking-friendly communities can enhance interpersonal communication and provide people a sense of belonging. Walking-friendly cities are conducive to creating more reasonable land use patterns and lower carbon urban transportation patterns. Fuelled by the increasing benefits and emphasis on the walkability of urban streets (termed "WoUS" in this paper), designing human-oriented street space has become one of the crucial environmental improvement strategies for competitive cities. Various initiatives have been proposed for streets, such as Green Streets in Portland, Street Design Guidelines in California. With this background, recent years have seen the emergence of several street environment evaluation platforms like

the SPACES (Systematics Pedestrian and Cycling Environmental Scan), the St. Louis Instrument in America, and the SWAT (the Scottish walkability Assessment Tool) in the UK. The widespread street policies and platforms indicate a global consensus on highlighting WoUS. The emerging deep learning algorithms for processing street view images and GIS analysis of environmental sensors' data shed light on evaluating the street walkability. This paper builds a methodology to evaluate both physical and perceived WoUS, conducted an empirical study of streets around a university campus as a test, and explored the feasibility and limitations of the methods.

## RELATED WORK

### *Defining "walkability of urban streets" (WoUS)*

In the late 1990s, the concept of walkability was first proposed in transportation research in the United States, which covers the built environment dimension related to pedestrian traffic. Since then, walkability has been defined differently in various fields such as urban planning, transportation planning, and public health due to differences in concerns.

According to different research scales, the research on walkability can be divided into urban walkability and street walkability. Southworth (2005) defines walkability as the capacity of a built environment that supports and encourages walking by providing for pedestrian comfort and safety, connecting people with varied destinations within a reasonable amount of time and effort, and offering visual interest in journeys throughout the network. Ewing et al. (2009) define walkability as the feeling of pedestrians walking in a street space. In this paper, the concept of 'walkability of urban streets' is used to address the extent to which the street environment and street form support walking. The support of the street environment includes street design elements such as street space quality, service facility level, landscape environment quality, etc. The support of street form includes providing pedestrians with possible walking opportunities and convenient travel paths, enabling pedestrians to reach various destinations within reasonable time and cost. The walking behavior of residents and the walking experience of pedestrians can be the results that reflect the street walkability.

### *Key impact factors for WoUS*

Streets are the product of urban public space and multidisciplinary integration. Based on the different cognitive methods of street walkability, different types of measurement system indicators constructed by various researchers have a different emphasis, and the interpretation of a single index is not the same.

In the field of urban design, early research on street walkability is point-like and single-dimension. The mostly used research methods are descriptive qualitative methods, and the research scale is micro-scale from the perspective of human cognition. The early research focuses on some built environmental factors that affect the comfort of the walking experience, such as sunlight, wind speed, road connectivity, building facades, etc. In recent years, researchers have begun to shift to networked research, from the perspective of spatial environmental indicators. They have started trying to use new digital methods, such as GIS and Google Street View, on larger-scale quantitative analysis and research about relevant elements of pedestrian networks, such as street intersection density, Building Near-Line Rate. As a result, some factors that were previously thought to be unrelated to walkability, such as land-use patterns, destination service facilities, and residential area density, began to show a positive correlation.

In the field of transportation planning, there are two different scale models on street walkability research. One is a macro-model based on traffic capacity, focusing on factors such as pedestrian flow and density. The other is a micro-model based on the evaluation of the Pedestrian Level of Services, focusing on walking facilities and walking environments, such as signs, lighting, and street crossing facilities.

In the field of public health, from the perspective of walking convenience and residents' activities, research on street walkability focuses on the acces-

sibility of walking space in community life and adds a comprehensive evaluation of community activity spaces and facilities. The research scope is limited to the neighborhood scale.

### *Key methods for measuring WoUS*

**Measuring WoUS based on the index system.** The development of index system evaluation methods is relatively mature. Walking index data is usually obtained by questionnaires and field surveys. The weights of corresponding indexes are rated by the expert panel. At the beginning of the 21st century, European and American countries have successively developed various index systems for urban walkability evaluation, such as 'PedestrianEnvironment Review System (PERS),' 'Rate my street,' 'Walkonomics' and 'Walkability Asia' (Liu et al. 2018). The different index systems do not have the same evaluation rules because of various types of communities or neighbourhoods. Among them, 'Walkscore' is accepted by many scholars with great influence in North American countries and New Zealand. Although the WoUS measurement method based on the index system includes indexes of multiple dimensions, its overreliance on the design of the questionnaire leads to the lack of accuracy of the survey results. The expert scoring method also lacks empirical evidence for the adjustment of the weight between different indicators.

**Measuring WoUS based on perceived data.** The WoUS measurement based on perceived data can be divided into two ways: interviews or records of interviewees' descriptions of street walking environments (McGinn et al. 2007) and observations of interviewees' preferences for street paths in cities (Sallis et al. 1997). Based on oral speech and semantic differences, the former usually uses methods such as interviews, questionnaire surveys and online scoring systems. The latter is human-oriented and has a detailed and meticulous measure of the psychological cognition of walkers. The measurement of pedestrians' perception of behavior has apparent advantages in personalization, diversity, and accurate analysis of individual differences. However, due to the limitation of labor cost, the sample size is often insufficient, and the collected detailed perceived data are difficult to standardize. It is only suitable for small-scale refinement research and not easy to replicate or promote in different regions.

**Measuring WoUS based on urban big data.** At present, some scholars have discovered that street-level greenness and buildings also influence residents' walking behavior (Yin et al. 2016) by using Google Street View and semantic segmentation the Street View images (Wang et al. 2019). The street walkability measurement method based on big data can uniformly measure the street walking space on a city scale at one time (Tang et al. 2016), and solves the shortcomings of insufficient sample size and inconsistent scale of manual evaluation (Curtis et al. 2013). However, the current research on the walkability of urban streets based on the big data method is still in its infancy. Currently, the types of big data that can be collected are relatively single, and most of them are single-dimensional urban big data. The calculation results often represent only one aspect of the street walkability and lack comprehensiveness.

Based on the above understandings, this research proposes a comprehensive approach for evaluation of WoUS with general applicability, not only with the automated recognition of the physical WoUS based on index system and big data to reduce subjective bias but also with the traditional subjective scoring.

## METHODOLOGY

Our research is conducted within Osaka University Suita Campus and Osaka University Hospital with an area of about 1.6 $km^2$. The land use of the study area is relatively simple, and most of them are education, medical and sports land. The roads are clearly defined, and there is a rail transit station on the east side. For students and patients who are the leading activity group in the study area, walking is their preferred mode of travel. The walking environment in this area has a significant influence on their daily trip

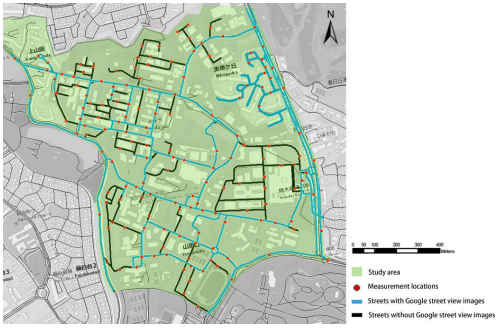
and life quality. Currently, unlike commercial and residential zones, little has been seen in the research on the street walkability of public zones such as education areas.

### *Data collection*

**Road network data.** We collect vector road network data to generate a road map from Open Street Map (OSM, www.openstreetmap.org), and all of the roads have been simplified into single-line streets using QGIS.

**POI (Point of interest) data.** POI (point of interest) data represents points of interest in the map and contains information on four aspects: name, type, longitude, and latitude. We used Python to download POI data of facilities in a radius of 4000m of the study area center from Google Maps and then refers to the WalkScore facility classification standard to reclassified the POI data into nine categories, such as schools, bookstores, and parks (Table 1).

**Street view images.** Based on the road map, we set our sampling points 35m apart on each road. In our street view dataset, each sampling point captured street view images from four directions (0, 90, 180, and 270 degrees). We obtained a total of 2912 street view images in the study area. In the streets without Google street view images of the study area, we use panoramic cameras to get street view images as a supplement.




**Measurement data.** Fig. 1 illustrates 170 measurement locations, and each location represents different characteristics of each street in the study area. The measurement data includes traffic flow data and environmental data. The measurement was conducted on March 11-12, 16-20, and 23-25, 2020, for a total of 10 days. The measurement time of traffic flow and the acoustic environment is in the morning (7:00-9:00) and noon (11:00-13:00), including peak and off-peak hours. The measurement time of the light environment is in the night (19:00-21:00).

Field counting and video recording are used to collect the traffic flow data at each measurement location. In the record, the camera tries to shoot all the scenes of the observed street in a vertical direction, including numbers and flow density of pedestrians. In this case, the underlying assumption is that more walking should be correlated with more walkable environments (Moura et al. 2017).

In this paper, the environmental data includes the acoustic environment and the light environment. Sound level meter (unit: dB) and illuminance meter (unit: lux) are used as measurement instruments. The noise evaluation of streets uses the acoustic objective physical index LAeq value as the acoustic environment evaluation index. The sound pressure level measurement was performed at each measurement location. The measurement time was 5 minutes, and the sampling interval was 1 second. The evaluation of street light environment mainly considers the night light level of the street which is represented by horizontal illumination. The measurement method is as follows. First, divide the entire street into several small rectangular spaces according to the position of the street lamp. Then, measure the horizontal illumination values of the four vertices of each rectangle. By calculating the mean of all the vertices, we can get the average horizontal illumination value of the street.

Figure 1
Road network and measurement locations of the study area

### *Workflow*

Fuelled by the above data, a method framework is built containing three main parts (Fig. 2). Both phys-

ical and perceived walkability are considered in the street walkability evaluation.

Automatic evaluation of physical WoUS is done by selecting the typical physical feature variables, exploring an auto-calculated approach with the support of 3-dimensional composition calculation, including deep-learning image segmentation technology, and 2-dimensional GIS analysis. Walkscore, greenery, enclosure, relative walking width, traffic flow, noise, and light are taken as the representative elements; these seven measurable aspects are selected according to the literature review and their capacity as measurable aspects, to demonstrate the methodology. After this, these seven indicators results are combined into one index using analytic hierarchy process (AHP) and questionnaire to represent the physical WoUS.

Subjective evaluation of perceived WoUS is the score of the willingness of street users to walk in the space, sampled from urban designers and borrowing widely accepted evaluation criteria from existing literature. This study uses feasibility, accessibility, safety, comfort, and pleasurability as its standards and compares the physical WoUS with the perceived WoUS as a verification process.

Table 1
Facility classification table

| Facility classification | Place types of Google place API | Weight |
|---|---|---|
| Grocery store | 'supermarket', 'convenience_store' | 3 |
| Restaurant | 'restaurant', 'bakery' | 3 |
| Shop | 'shopping_mall','bicycle_store','shoe_store','store','pet_store','liquor_store','hardware_store','jewelry_store','clothing_store','furniture_store','home_goods_store' | 2 |
| Cafe | 'cafe','night_club','bar' | 2 |
| Bank | 'bank','atm' | 1 |
| Park | 'park','zoo | 1 |
| School | 'school' | 1 |
| Book store | 'library','book_store' | 1 |
| recreation | 'movie_theater','museum','gym','stadium','spa','hair_care','amusement_park','aquarium','art_gallery','beauty_salon' | 1 |

**Physical WoUS evaluation.** Considering integrating multidisciplinary measures and achieving an auto-calculable method, more effort is taken to construct an integrated method rather than construct a concrete and all-inclusive index system. Therefore, these seven important and measurable indicators are selected: the basic feature 'Walkscore,' 3D features including street greenery, enclosure and relative walking width, environmental features including noise and light level, and traffic features including flow density of pedestrian, bike, and car.

Walkscore is a typical function-oriented calculation method of street walkability, which reflects the connectivity of the street and service functions in the street. The calculation of Walkscore in this paper is generally performed in QGIS with reference to the Walk Score company (www.walkscore.com). First, construct a network data set in QGIS based on 1588 POIs data and OSM road network data. Then, calculate the number of various types of facilities within the walking range of 400m, 800m, 1200m, 1600m and 2000m of each sampling point on the street based on the facility classification table (Table 1). Finally, according to different walking ranges, we can obtain the Walkscore of each sample point by multiplying the corresponding distance attenuation coefficients and overlapping the weights, respectively, based on the Eq. (1):

$$S = \sum_{i=1}^{n} N_i \cdot W_n \cdot f(d)(1) \qquad (1)$$

where *S* is the walkscore of a sample point; n is facilities of classified types; *Ni* is the number of facilities; *Wn* is the weight in facility classification table; *d* is the distance between facility and sample points and *f(d)* is corresponding distance attenuation coefficients. In addition, this method is borrowed from Long et al. (2018) that simplifies the distance attenuation coefficient curve into a piecewise function: attenuation coefficient of 400m, 400m-800m, 800m-1200m, 1200m- 1600m and 1600m-2000m is 1, 0.9, 0.55, 0.25 and 0.08.

In this study, we used Deeplab (Chen et al. 2017) with street view images to calculate street greenery, street enclosure, and relative walking width. Many semantic pixel-width image segmentation methods based on convolutional networks have emerged recently, such as YOLO, ImageNet, SegNet, DeepLab,

and so on. DeepLab is highly accurate and easily accessible. Fig. 3 is a DeepLab segmentation testing sample.

All the downloaded street view images are interpreted into color groups using the DeepLab decoder. Nineteen kinds of physical components are obtained, namely road, sidewalk, building, wall, fence, pole, traffic light, traffic sign, vegetation, terrain, sky, person, rider, car, truck, bus, train, motorcycle and bicycle. We summarize percentages of each component in the four-directional dataset (2912 images for 728 locations from Google Street View and 170 images from a panoramic camera) are summarized, and the mean value for each location is calculated to represent the average condition of that location. Then the percentage of trees as greenery (Eq. (2)), sky ratio as enclosure (Eq. (3)), and pavement to road ratio as relative walking width (Eq. (4)) are used for evaluation.

$$P_{green} = \frac{\sum_{i=1}^{4} GP_i}{\sum_{i=1}^{4} P_i} \quad (2)$$

$$P_{enclosure} = \frac{\sum_{i=1}^{4} SP_i}{\sum_{i=1}^{4} P_i} \quad (3)$$

$$P_{width} = \frac{\sum_{i=1}^{4} PP_i}{\sum_{i=1}^{4} RP_i} \quad (4)$$

where *GPi* is the number of greenery pixels in image i; *SPi* is the number of sky pixels in image i; *PPi* is the number of pavement pixels in image i; *RPi* is the number of road pixels in image i and *Pi* is the total number of pixels in image i.

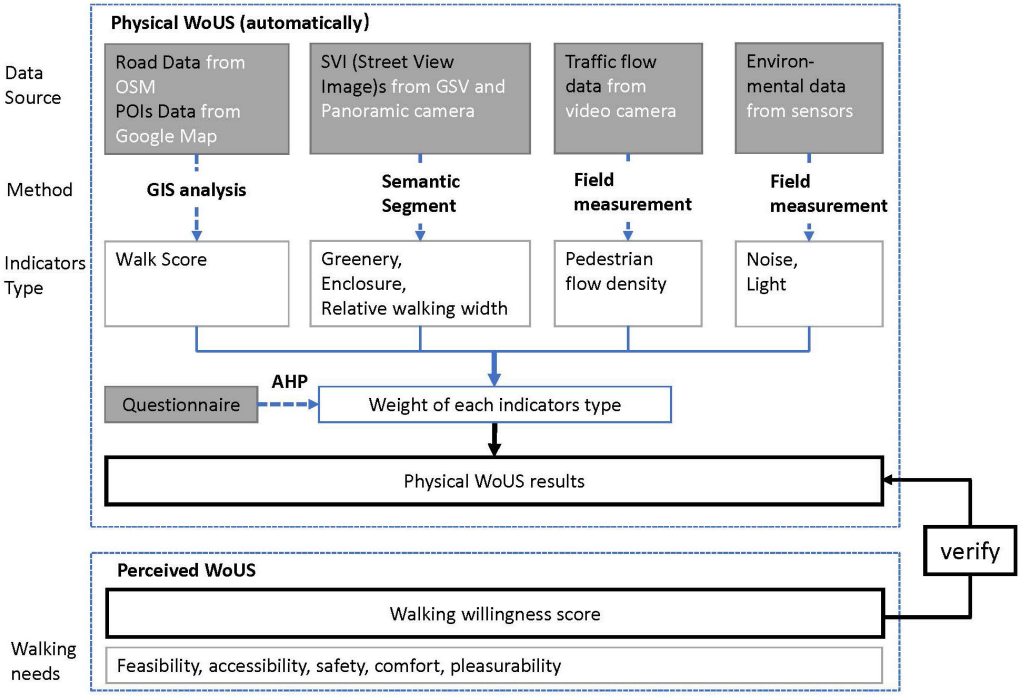



Figure 2
The framework of the study

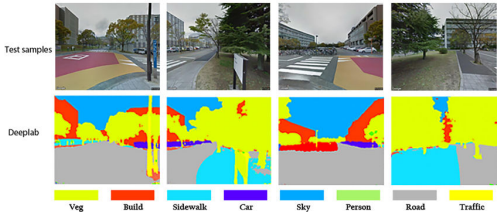



Figure 3
Deeplab segmentation testing sample (location: lat:34.81760, lon:135.52118)

In addition, the method of measurement data collection was introduced in the previous section. All the traffic flow data were imported into QGIS with coordinate information as well as the environmental data of noise and light.

To summarize the physical WoUS into one index, firstly, we have standardized the results of the above indicators into 1 to 5. Then, an analytic hierarchy process (AHP) approach was used to calculate the weighting for each indicator using a pairwise comparison by questionnaire. AHP requires a number of assessors to determine the relative importance of indicators by comparing them in pairs. This makes the results more reliable and reduces potential decision errors. Twenty students of urban design education background and twenty people of communities were involved in the questionnaire survey, the results of which are presented in Table 2. In the questionnaire, interviewees were asked to consider indicator weights of physical WoUS and perform a pairwise comparison on each two of them, including Walkscore, greenery, enclosure, relative walking width, traffic flow, noise, and light.

**Evaluation of perceived WoUS (walking willingness scoring).** In this study, the willingness to walk (in the street) is scored by urban designers to measure the overall perceived WoUS directly. The five levels of need represent the precursors within the walking decision-making process and the key aspects of perceived WoUS (Fig. 5), integrating criteria from Alfonzo (2005) and London Planning Advisory Committee (Gardner et al. 1996) which has been widely adopted to the present (Sidawi et al. 2013). These levels are feasibility, accessibility, safety, comfort, and pleasurability. In order to clearly make a comparison with the physical WoUS result, they are summarized into one index, called the 'walking willingness score.'

According to literature, feasibility refers to a walking trip feasible in relation to mobility, time, or other responsibilities. It is related to the diversity of land uses and functions conveniently accessible on foot. The meaning of accessibility is that the actual or perceived barriers to walking are sidewalks, paths, or features present, and destinations are within a reasonable distance. Safety, which describes that does a person feel safe from the threat of crime and traffic accidents in the physical street space, could affect psychological feelings through changes in architectural details, pavement forms, types of land use, and so on. Comfort means that the street space provides satisfaction or contentment with attributes and amenities that ease all types of pedestrians' walking experience. Pleasurability measures the level of appeal that the walking routes are discernible, and public space is diverse, lively, enjoyable, or interesting to walk in.

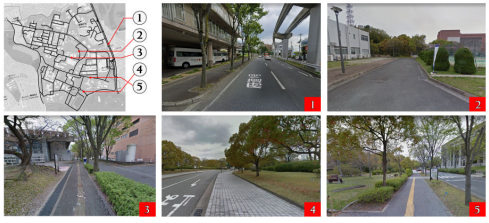



Figure 4
street view images samples for walking willingness score ranging from 1 to 5

Our four raters are all designers with a background in urban design education, and they were invited to comprehensively measure the WoUS from the above five levels by field survey, giving a score from 1 to 5. To avoid results from being affected by seasonal weather and subjective bias, they firstly scored together to have a consensus of the criteria, and then scored separately. Fig. 4 shows the sample street view images for different walking willingness scores.

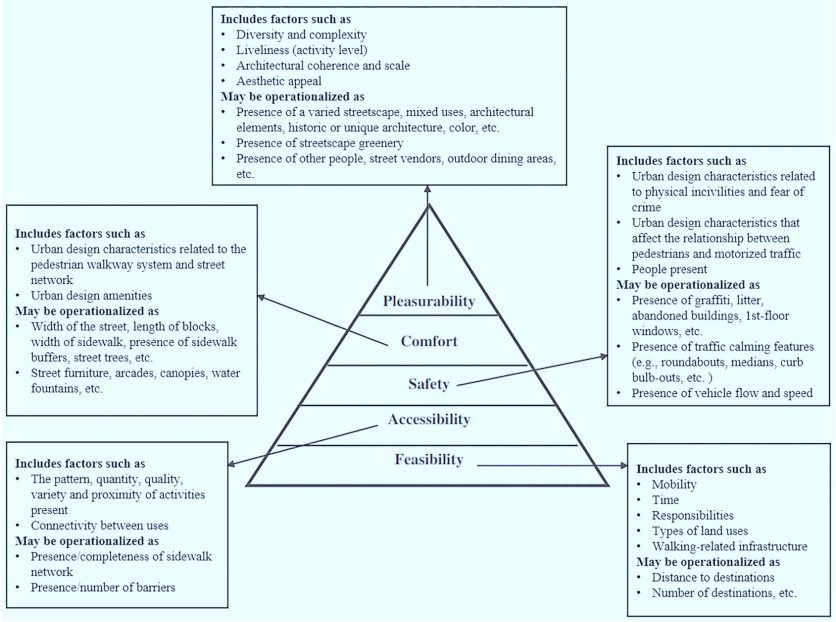



Figure 5
Hierarchy of walking needs model

## RESULTS

### *Street walkability of the study area: Physical features*

After implementing the proposed model in the study area, the following results were obtained. Fig 6 (a) shows the final seven-aspect physical WoUS index result, and Fig. 6 (c) shows the seven physical features' results separately. The average physical walkability index score is 2.26. High score areas are around: (1) rail transit stations, (2) Expo'70 Commemorative Park, (3) Osaka University Hospital, (4) stadiums, and (5) canteens. It can be concluded that the streets near the large public service facilities have better physical WoUS. These areas often have better locations as well as spatial qualities and gather relatively high-density people, who need to take more consideration of street walkability. It is not difficult to see that these streets often have higher street greening levels, higher relative walking widths, higher night light environment levels, and lower street enclosures. Due to intensive traffic flow and environmental noise, the walkability of municipal streets is significantly lower than the walkability of streets of campus. In addition, areas with relatively high intersection density, have a higher Walkscore and walkability than areas with low intersection density. This shows that the road network has affected the walkability of the street to a certain extent.

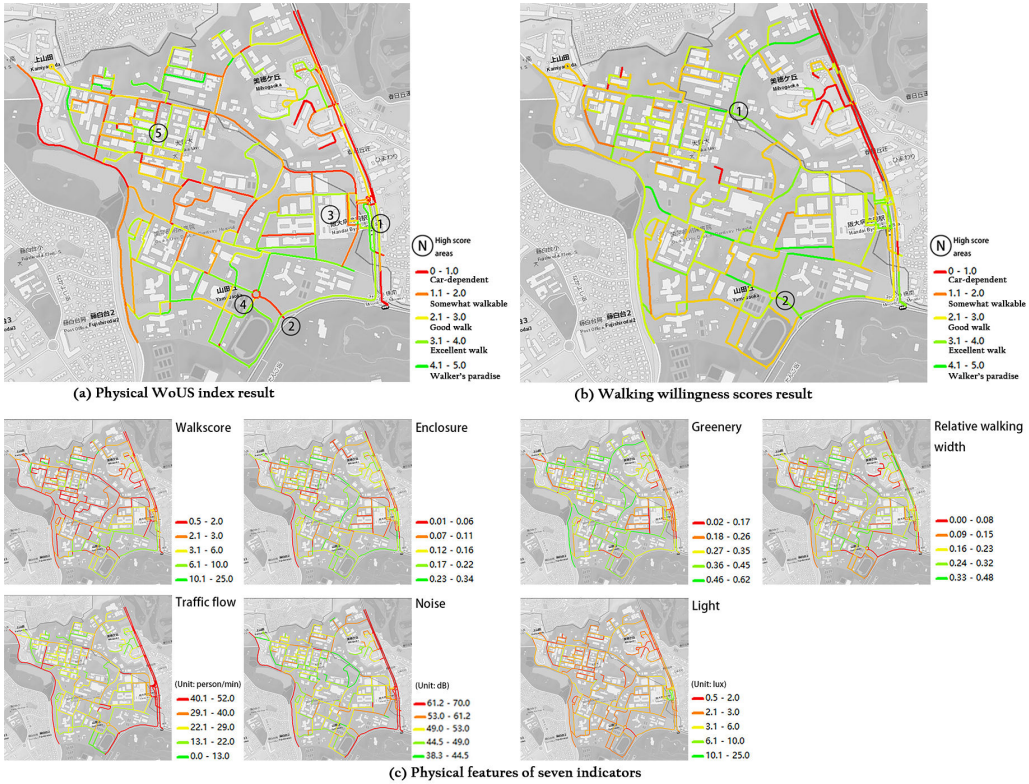
### *Street walkability of the study area: Perceived walking willingness*

Fig. 6 (b) shows the overall Perceived walking willingness scores of streets. The average score is 2.67, where only 3% are rated 5, and 9% are rated 1.

| Indicators of physical WoUS | Walkscore | Greenery | Enclosure | Relative walking width | Traffic flow | Noise | Light |
|---|---|---|---|---|---|---|---|
| Weight | 0.4619 | 0.0505 | 0.0197 | 0.0840 | 0.1946 | 0.0479 | 0.1414 |

Table 2
physical WoUS evaluation indicator weightings

Figure 6
Physical and Perceived WoUS results




(a) Physical WoUS index result

(b) Walking willingness scores result

(c) Physical features of seven indicators

Most streets are rated 2 or 3, accounting for 38.2% and 32.1%, respectively. Taking the perceived WoUS rated by educated designers as the benchmark, there is relatively fair agreement as well as a discrepancy between perceived and physical WoUS. The results are verified by comparing high scoring areas with site visits: it was found that the index could tell the feasibility and accessibility but could not reflect the comprehensive walkability, since perceived WoUS near (1) landscape lake and (2) school gate are high though they have low walkscore. Results show that the main contributing factor to the difference between the approaches is the level of ignorance of some aspects related to walking pleasurability and comfort, such as the level of aesthetic appeal, numbers of street furniture and streets slope; while these factors are important indicators for subjective evaluation, they are missing from automated evaluation, leaving a gap for further research.

## CONCLUSION AND DISCUSSION

This study proposed an evaluation framework for WoUS, including physical and perceived WoUS. The first was calculated automatically with the support of QGIS, Deeplab, and AHP, while the latter was achieved quantitatively through a rating system based on systematic indicators. An empirical study of Osaka University shows that, although the street

walkability on campus is significantly higher than that of municipal streets, the general walkability fails to satisfy the current needs, remaining to be improved.

It is an initial attempt to construct a quantitative research methodology for WoUS. After testing, this methodology shows its feasibility and convenience for preliminary investigation of urban design, suggesting potential application as an augmented tool for designers. In addition, the walkability evaluation process also shows its potential use in stimulating participative planning. With a variety of evaluation platforms, walkability can be rated directly by the residents, promoting users to express their expectations for the environment and forming a walkability-oriented route recommendation system.

While appreciating the merits of this study, there are still several limitations deserving further research in the near future. First, the concept of walkability is human-dependent (subjective), considering its nature, based on sensation and perception. The scoring index for the walkability of street space may vary among different people groups, and the determination of weights of seven indicators is still waiting for further comprehensive discussions. Second, Although it is helpful to reflect the real situation of different dimensions of the walking environment by adding environmental surveys and field observations, it also limits this method to be extended to large-scale urban street evaluation.

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# D2.T9.S1. CULTURE /SHIFT THROUGH UBIQUITOUS COMPUTING/SCRIPTING AND LINGUA FRANCA

# Local Adaptation of the International Style

## *Contextualizing Global Architecture between East and West*

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*The aim of this paper is to highlight the effectiveness of shape grammar as a computational design methodology for verifying and describing hybridity in architectural design and generating a contextualized architecture. Part of a larger study, the present paper focuses on describing and verifying the respective influences of European modern and American traditional architecture on the mid-twentieth-century houses designed and built by a Penn State faculty-practitioner in State College, a college town in central Pennsylvania that is home to the university's largest campus. This hybridity phenomenon is analyzed using the shape grammar methodology, which is then also used to generate a hybrid architecture, not only for the same context, but also for contexts worldwide. Results from a workshop on the local adaptation of modern architecture focusing on the hybridity between the Persian garden style and the International Style of architecture to generate architecture appropriate to the context of Shiraz, the ancient capital of Iran, are analyzed in order to advance discussions of the methodology.*

**Keywords:** *Shape grammar, Persian garden, William Hajjar, Hybridity, local adaptation*

### *Introduction*

International Style architecture has been criticized because of its placelessness. Yet, in the mid-twentieth-century period, architects worldwide, especially outside Europe-the birthplace of both modernism and the International Style-sought to adapt International Style modernism to the local context in which they were practicing. In the process of documenting examples of mid-twentieth-century architecture in a few college towns on the East Coast of the United States, including State College, PA, the authors observed that the residential architecture of William Hajjar, a member of Penn State's architecture faculty in the mid-twentieth-century period, incorporates many of the shapes and features of both European modern architecture and American traditional architecture. It was discovered that this distinctive quality-which helped popularize modernism in the United States-can also be found in the work of his fellow faculty-practitioners in other U.S. college towns. Highlighting this hybridity between European modern architecture and American traditional architec-

ture in Hajjar's work with shape grammar used as a computational design methodology, the present paper-as part of a larger study-explores a systematic approach to both analyzing hybridity in architectural design and generating a hybrid architecture as a way to adapt the International Style architecture (and by extension any given architectural style) to a local context.

The theoretical outcomes of this study answer this fundamentally important question regarding the methodology and the context: Can shape grammars be used to verify and describe architectural hybridity between modern and traditional architecture either overall or in specific contexts? Although beyond the scope of this study, the ultimate goal is to use this analysis as a foundation for considering styles of architecture across all eras. Two possible avenues in this regard are (1) to consider the architecture of the past in order to show how architecture evolves through a hybridization process and (2) to imagine an architecture of the future by applying a process of hybridization to generate new architectural styles appropriate to a given context.

## *Methodology*

The present paper is part of a larger-scale project in which shape grammar is used to verify and describe hybridity between European modern architecture and American traditional architecture, with Hajjar's architecture featured as a case study. The steps taken in performing this analysis are as follows: (1) Hajjar's life and practice are traced to identify likely influences on his work; (2) a shape grammar is developed for the houses he designed for and built in State College; (3) the grammars of some of the likely influences on his work are developed; (4) Hajjar's grammar is compared to the grammars of these influences to determine the nature and extent of their impact on his work; and (5) aspects of the social and technological context that may explain such influences are identified-i.e., trends in regard to lifestyle and the availability of materials and technologies.

In previous papers, the authors described and analyzed Hajjar's single-family architecture (Hadighi & Duarte, 2018), European architecture, and the Bauhaus style through the work of Gropius and/or Breuer in the US (Hadighi & Duarte, 2019a), and the traditional architecture of the State College area(Hadighi & Duarte, 2019b). These analyses were performed by developing shape grammars of Hajjar's single-family houses in State College, Gropius and/or Breuer's houses in the United States, and the traditional American architecture of the context in which Hajjar's work evolved. In the present paper, the authors focus on learning from architectural hybridization through comparing and contrasting shape grammars in order to generate a hybrid and contextualized architecture. Future papers will focus on other methodological steps related to the notion of hybridity.

## *Shape Grammar*

Shape grammars in computation are a specific class of production systems based on an initial shape, or a set of finite shapes, and transformational shape rules (Stiny & Gips, 1971). Since the 1970s, as a computational design theory, the concept of shape grammar has been used in architectural analysis when a pattern of design characteristics or a stylistic repetition of shapes in architecture is evident. This theory has been used in relation to many examples of historical architecture, such as Palladian villas as analyzed by Stiny and Mitchell (1978), Frank Lloyd Wright's Prairie houses as analyzed by Koning and Elizenberg (1981), bungalow houses as analyzed by Downing and Flemming (1981), Queen Anne houses as analyzed by Flemming (1987), and Alvaro Siza's houses at Malagueira as analyzed by Duarte (2005).

In the past three decades, to a certain extent the idea of comparing grammars and the notion of stylistic evolution has been explored in multiple ways in the literature. For example, such comparisons have been used in endeavors to explain the evolution of art and architecture in the work of a given artist or architect (Knight, 1994); to define composite grammar-i.e., a grammar in which languages are integrated

and thus transformed-as a framework for analyzing the evolution of historical architecture (Chase & Ahmad, 2005); the influence of Alberti's Treatise on Architecture on Portuguese Renaissance architecture (Figueiredo et al., 2014; Kruger et al., 2011); to enable the adaptation of existing traditional houses to new requirements (Eloy & Duarte, 2014); and to generate a generic housing grammar from three existing grammars (Benros, 2018). However, in the present paper, this methodology is used to verify and describe-in both qualitative and quantitative terms-hybridity in architectural design and in local adaptations of European modern architecture.

### *William Hajjar*

Abraham William Hajjar (1917-2000) was a faculty member and researcher in architecture at the Pennsylvania State University in the mid-twentieth century and a practitioner in the local town of State College, PA. Hajjar studied architecture at the Carnegie Institute (now Carnegie Mellon) (1936-1940) and at the Massachusetts Institute of Technology (MIT) (1940-1941). Then, after teaching for a few years at the State College of Washington, he became a faculty member at the Pennsylvania State College (now the Pennsylvania State University or simply Penn State) (1946-1963) and a practitioner in the area (1952-1963). At Penn State, he focused on securing tenure for a number of years. However, from 1952, when the first house he designed for State College was built in the area, to 1963, when he moved to Philadelphia on a leave of absence from Penn State to work with Vince King, a friend from MIT and a successful Philadelphia architect, Hajjar designed and built thirty-three single-family houses in the Penn State area.

In the late 1930s, Hajjar was at the Carnegie Institute, where the school of architecture, like most architecture programs in the country, was dominated by the Beaux-Arts. However, he also came into contact with some of the young faculty members teaching freshman and sophomore studios who favored a modernist design philosophy. In addition, and perhaps, critically, Walter Gropius, who had immigrated to the United States to direct the architecture program at Harvard, delivered a lecture at the Carnegie Institute in 1938, when Hajjar was a sophomore. This was probably Hajjar's first opportunity to interact with Gropius, although we do not know if the two actually met at this time.

While at MIT, Hajjar became well-versed in modernist design under the supervision of Lawrence Anderson, who was among a number of faculty members advocating for modern architecture at MIT during the 1930s. More importantly, it is likely that Hajjar was influenced by modernist ideas propagated by the German émigrés: He was at MIT when Gropius and Breuer were at Harvard, a time when students from the two schools attended lectures together and when Anderson would often invite Gropius, Breuer, and other outside critics to MIT to review the students' work (Anderson, 1992). Also, while Hajjar was at MIT, the architecture program collaborated with Harvard on a summer semester design project whereby a class from each institute, probably a small number of students, rented a house in the cape where they lived and worked on a project together. These collaborations between MIT and Harvard introduced Hajjar and also his fellow students to Gropius's architectural philosophy.

At the time Hajjar moved to State College, most single-family residences in the area were in the Georgian revival, Colonia revival, Tudor, and Cape Cod styles, although ranch and split-level houses were also starting to appear. Hajjar's first design in State College was his own family home/office in the College Heights district. His initial work in the State College area was mainly in the College Heights neighborhood situated immediately northwest of the Penn State campus and in the Holmes-Foster neighborhood situated to the southwest of the campus. Some of the houses he designed in these neighborhoods, especially the earliest houses, consist of a core shoe box design element. The shoe box could be long or short, parallel or perpendicular to the main road, but most had a low-pitched roof that could be symmetrical or asymmetrical. Most have a garage (mostly

with a flat roof) connected to the main house with a breezeway, although by now many of the breezeways have been altered to accommodate an enclosed addition. Most of the time, the main entrance of the house is through this breezeway. In fact, the entrances to Hajjar's houses are generally hidden, either through the breezeway or at the side.

Through a consideration of the volumetric relationship, the spatial organization, and the main features of Hajjar's single-family houses in the area, five subtypes in his plans have been identified. As explained, in most of the houses, a signature feature is evident between the main volume, the garage (or a secondary inhabitable space), and the breezeway. In general, the grammar of the single-family houses designed by Hajjar in mid-twentieth-century State College was developed based on the five subtypes described. Further, the grammar encompasses four phases or groups of rules:

- Rules to capture the way in which Hajjar situated his houses on the lots.
- Rules to describe the formal relationships between mass volumes.
- Rules to describe the way in which the interior space is divided into smaller rooms or spaces and the way in which functions are allocated.
- Rules to generate details such as wall thickness and the placement of closets.

A detailed account of the development of the grammar for Hajjar's work is available in a previous paper by the authors (Hadighi & Duarte, 2018). The grammar can both produce all the houses that Hajjar designed in the area and generate new designs based on Hajjar's architectural language. Figure 1 shows selected rules of Hajjar's grammar.

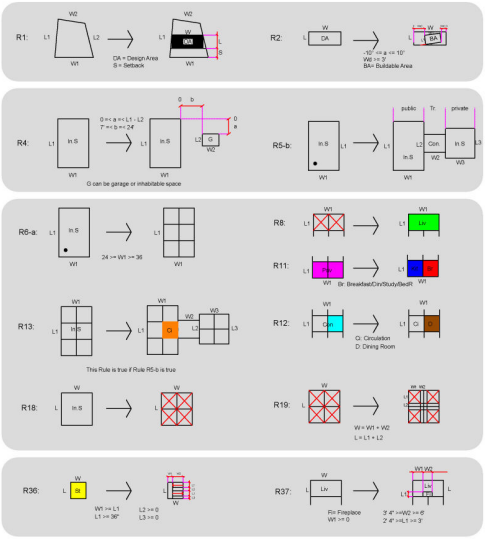



Figure 1
Selected rules of the grammar for Hajjar's architecture.

### *European Modernism of Walter Gropius and Marcel Breuer*

By the time World War II broke out, most members of the Bauhaus had already left Germany. Many were teaching at major schools in the United States, where they were to influence an entire generation of American artists and architects. Harvard's Graduate School of Design (GSD) was the first school in the nation to officially train students in modernist architecture with the appointment of Gropius as the director of the Department of Architecture in 1937. Soon, Marcel Breuer joined Gropius in the US, and the two taught together at Harvard and formed a brief architectural partnership. It is worth adding here that the period Gropius and Breuer spent teaching at Harvard and likewise the period that van der Rohe spent teaching at the Illinois Institute of Technology (IIT) marked "the beginning of systematic training in modern principles in American architectural education" (Jordy, 1968).

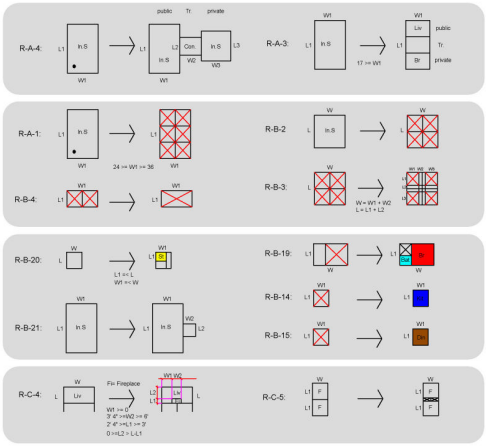
In Germany, Gropius had focused on large-scale buildings, such as apartment buildings and institutional projects. The only residential house he

Figure 2
Selected rules of the grammar for Gropius and/or Breuer's houses in the US.

had designed in that country were the "Masters' Houses," a group of combined single-family houses for the Bauhaus teachers, commissioned by the City of Dessau in 1925-1926. It was not until his move to the US that Gropius turned his attention to designing single-family houses. In 1937, with Breuer, he designed his first house, Gropius House, for his own family in Lincoln, MA, with the construction ending in 1938. Modest in scale in comparison to other houses in the area, Gropius House was revolutionary in terms of its impact. The house incorporates traditional elements of New England architecture, such as wood, brick, and local stone, combined with modern materials, such as glass block, acoustical plaster, and chrome banisters. A National Historic Landmark, Gropius House is the posterchild for localized Bauhausian architecture in the New England area and in the United States more generally.

Gropius commented that after moving to the United States and becoming well known, "I realized that I am a figure covered with labels, maybe to the point of obscurity" (Gropius, 1962, p. 11). He was referring to labels such as "Bauhaus Style," "International Style," and "Functional Style," which, as he noted, "have almost succeeded in hiding the human core behind it all." He was, therefore, eager "to put a few cracks into this dummy that busy people have slipped around" him (Gropius, 1962, p. 11).

Similar to the process used to develop a grammar based on Hajjar's projects in State College, PA, all the single-family houses designed by Gropius and/or Breuer in the United States are analyzed with an emphasis on their volumetric relationship, spatial organization, and defining architectural features. A detailed account of the development of the grammar for Gropius and/or Breuer's work in the United States is available in a previous paper by the authors (Hadighi & Duarte, 2019). The grammar can both produce all the houses that Gropius and/or Breuer designed in the United States and generate new designs based on their architectural language. Figure 2 shows selected rules of the Gropius Breuer grammar.




## *Traditional Architecture of the Context*

The college town as an American phenomenon is a community that is heavily dependent on the university it hosts. College towns have characteristics in common with both small towns and cities: In terms of population, urban settings and urban infrastructure, they are more comparable to other kinds of small towns. In terms of culture and education, they are more comparable to large cities.

Located in central Pennsylvania, State College is a college town dominated both economically and demographically by the University Park campus of Pennsylvania State University (Penn State). Evolving from a village to serve the needs of the Pennsylvania State College (founded as the Farmers' High School of Pennsylvania in 1855), State College was incorporated as a borough in 1896. Expanding with the growth of the university, the neighborhoods adjacent to University Park campus initially developed in the early twentieth century. To study single-family domestic architecture designed in traditional styles in the area, it is instructive to explore the College Heights Historic District, a national historic district located north of campus that was added to the National Register of Historic Places in 1995.

College Heights encompasses land and historic

buildings associated with the early residential history of the town. Like all historic districts, College Heights has "contributing" and "non-contributing" properties. The registration form for College Heights indicates that the district has 278 contributing properties. Although all the contributing houses have a special characteristic(s) in relation to the history of the neighborhood, the registration document highlights some properties as the best examples of houses designed by local architects/contractors or offered by popular mail-order catalogues. Most of these examples, constructed in the 1920s and 1930s, are built in bungalow, colonial (Dutch and Georgian), colonial revival, Georgian revival, and foursquare styles.

To study the traditional architecture of the context in which Hajjar taught and practiced, a grammar is developed for traditional houses designated as contributing in the College House Historic District registration document. Similar to the grammar for Hajjar's single-family houses, the grammar for traditional American houses encompasses several groups of rules: rules to define the overall inhabitable space; rules to describe the way in which the interior space is divided into smaller spaces or rooms; rules to allocate the interior functions; and rules to generate details such as the placement of closets, the placement of a fireplace, and wall thickness. A detailed account of the development of the grammar for American traditional houses in the State College area is available in a previous paper by the authors (Hadighi & Duarte, 2019). The grammar can produce all the traditional houses in the corpus. Additionally, traditional plans that were not originally part of the corpus can be produced. Figure 3 shows selected rules of the grammar developed for the traditional houses of the context.

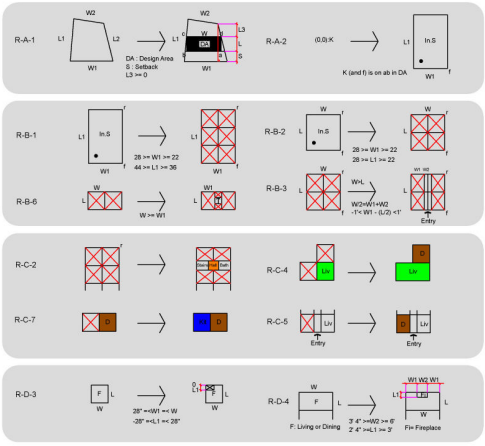
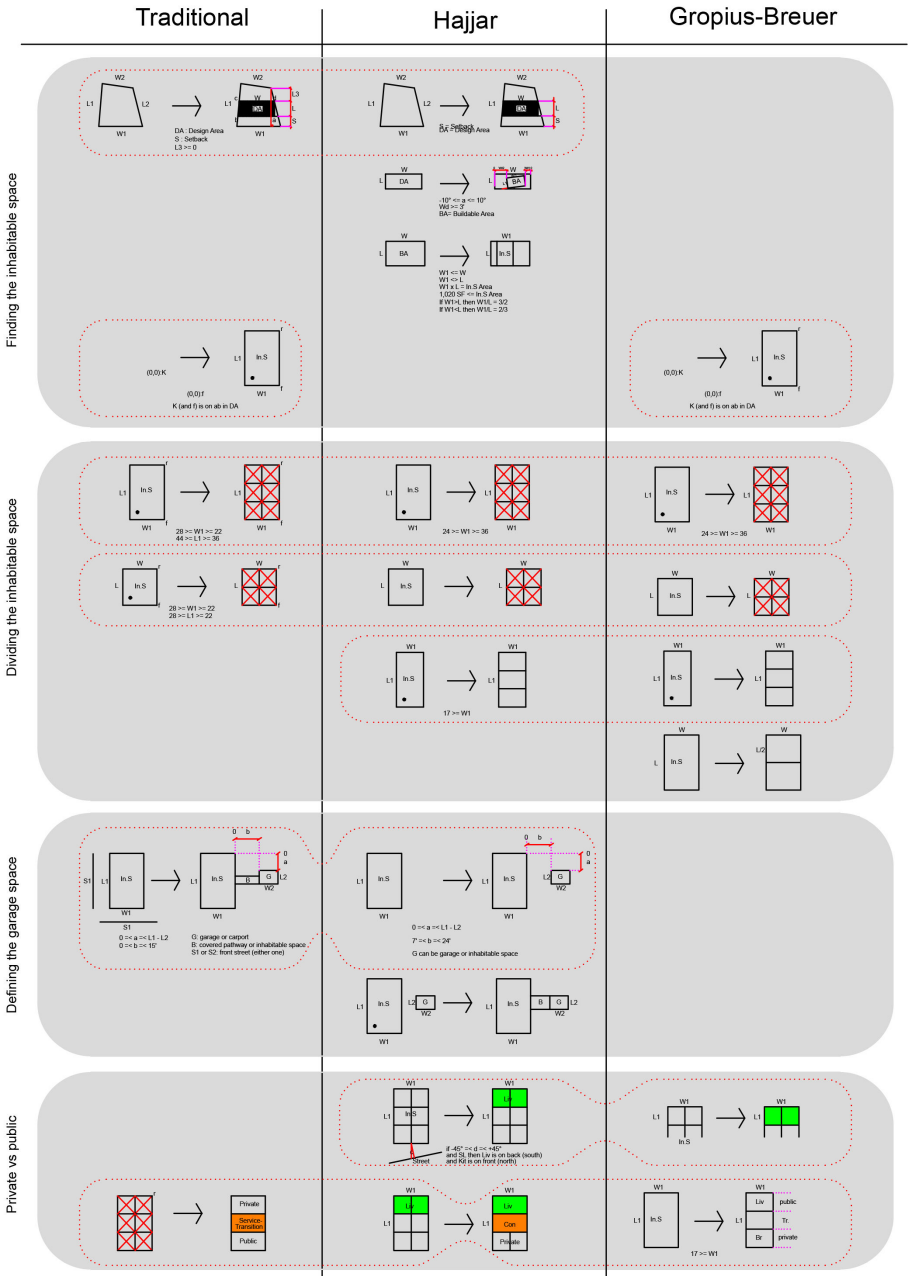



Figure 3
Selected rules of the grammar for traditional houses of the context

### *Local Adaptation of Modern Architecture*

In order to analyze the hybridity between the local context and European modern architecture in Hajjar's single-family houses, the three grammars developed for Hajjar's work in the State College area, Gropius's and/or Breuer's work in the United States, and the American traditional architecture of the context in which Hajjar taught and practiced are compared and contrasted. A detailed account of this comparison will be available in a separate paper. In order to consider the three grammars in relation to one another, it was necessary to compare and contrast the rules of each. The three grammars were developed following the same process and with the same level of detail, which made it possible to compare the rules on a like-with-like basis. The rules of the three grammars were organized according to categories such as rules for volumetric organization (finding the inhabitable space and garage space), rules for dividing the inhabitable space, and rules for interior organization-circulation (private vs public spaces). Then, the rules were compared to determine which rules in Hajjar's grammar were borrowed with or without adaptation from either or both of the other two grammars, which rules included in either or both of the other two grammars were excluded, and which rules were

Figure 4
Comparison of the finding the inhabitable space rules, dividing the inhabitable space rules, defining the garage space rules, and defining private vs. public rules of the grammars.



entirely new. Figure 4 shows an example of the comparison of the rules of the three grammars.

A comparison of the respective rules reveals the following: In relation to the Gropius-Breuer grammar, 54% of Hajjar's rules are either the same or show very minimal changes, 13% reflect an adaptation, and 33% are new rules. In relation to the traditional grammar, 29% of Hajjar's rules are the same, 17% reflect an adaptation, and 54% are new rules. In relation to Hajjar's generation of his own rules, 25% of the rules in his grammar are not used in either the Gropius-Breuer grammar or the traditional grammar. Finally, in relation to a comparison across all three grammars, 25% of the rules used by Hajjar are also the same in the other two grammars, meaning that the three grammars all have the same 25% of their rules in common. This 25% commonality does not necessarily indicate the influence of one grammar on the other two. Instead, it reflects the idea that a house is a house regardless of its designer, its style, or the time period in which it was built.

There are other effective ways of considering possible similarities between shape grammars, for example through a step-by-step comparison of their derivation-in this case between those of a house designed by Hajjar, a house designed by Gropius-Breuer, and a house from the traditional context. A third approach is to use a grammar to produce a house that was used to produce another grammar. For example, through a grammar of Hajjar's work, a Gropius-Breuer house (a house with a layout as close as possible to a Gropius-Breuer house) can be created that is then compared with the original Gropius-Breuer design and vice-versa. The same strategy can, of course, be used to compare Hajjar's grammar with the traditional grammar.

### *Generating Hybridity in Architectural Design: Contextualizing Global Architecture*

By explicating different approaches to comparing and contrasting the three grammars described in relation to analyzing hybridity in Hajjar's architecture, the authors sought to identify hybridity in architectural design in order to contextualize global/international architecture. Through this process, the rules of each grammar were established and the rules in common among the grammars identified. Similarly, rules that changed from one grammar to another were identified, as were new rules created for a given grammar and rules that were excluded from it. Through an analysis of the designs generated by the grammars in relation to each other, it was possible to establish the ways in which and the extent to which houses designed by a given architect ( in this case, Hajjar) can be generated by a grammar of an influential architect or an influential style of architecture ( in this case, Gropius and/or Breuer's architecture and American traditional architecture of the State College area). The results of the analysis demonstrate the effectiveness of shape grammar as a computational design methodology in verifying and describing hybridity in architectural design.

These analyses led the authors to consider the systematic approach presented in this paper for types and styles of architecture across all areas. As noted in the Introduction, two possible avenues in this regard are (1) to consider the architecture of the past in order to show that architecture evolves through a hybridization process and (2) to imagine an architecture of the future by applying a process of hybridization to generate new architectural styles appropriate to a given context. As a step toward this goal, the first author organized a workshop on the local adaptation of modern architecture focusing on the hybridity between the Persian Garden style and the International Style to generate architecture appropriate to Shiraz, the ancient capital of Iran. The workshop was hosted by Hafez University in Shiraz, Iran in 2019.

The aim of the workshop was to design a building to serve as Iran's pavilion for EXPO 2020. Although approaches to designing a pavilion to showcase their achievements will vary considerably across nations, most follow the theme of the expo while endeavoring to express cultural identity through the architectural language of their respective pavil-

Figure 6
Example of a group project designed by students in the workshop.

ions. The students participating in the workshop–21 graduate students of architecture and historic preservation–were assigned the task of designing a pavilion in the specific context of this expo as a hybrid architectural production in order to connect-in a meaningful and artistically satisfying way-the world's architecture/International Style with local Iranian architecture. In this regard, the theme of the Persian garden was chosen given that the workshop was offered in Shiraz, the birthplace of the Persian garden concept. The grammar previously developed for the Mughal garden by Stiny and Mitchell was analyzed in detail (1980), and the rules of that grammar were adapted for Persian gardens and specifically for the gardens in Shiraz. Using the grammar developed for the work of Gropius and/or Breuer described in this paper, the students focused on developing rules to express hybridity between the two grammars or architectural styles: the Persian garden and the modern architecture of Gropius and Breuer. Figures 5 and 6 are examples of the results of the workshop.

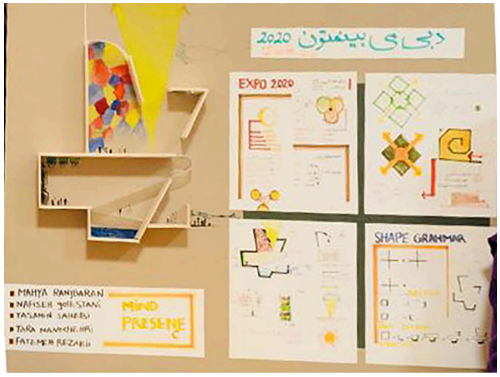
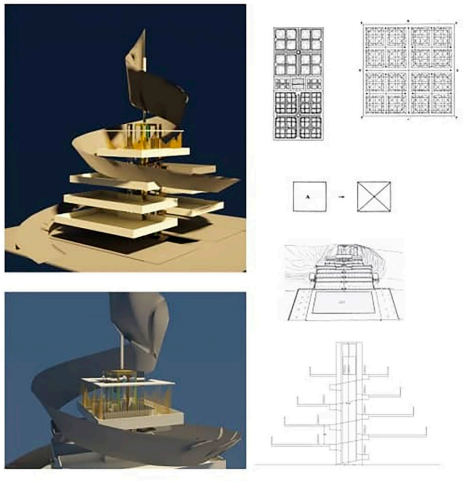



Figure 5
Example of a group project designed by students in the workshop.



## *Discussion*

An analysis of Hajjar's architectural language including through a comparison with Gropius/Breuer's architectural language and the American traditional architecture of the local context comprised the focus of this paper. Through these comparisons, the authors demonstrated the effectiveness of shape grammar as a computational design methodology in verifying and describing hybridity in architectural design. Further, this paper constitutes a step toward generating hybridity in architectural design. It is important to note, however, that this paper does not include a comparison of the socio-economic situations and technological limitations/innovations of the contexts in which the work examined herein evolved-i.e., Hajjar's domestic architecture, Gropius and Breuer's domestic architecture, and American traditional houses. However, these influences are reflected in the rules of the grammars used to analyze Hajjar's architectural language. Yet, in generating a new hybrid architecture, it is certainly reasonable to expect the socio-economic context and building technology available to be important in accounting for similarities and differences between the rules of any given grammars. The results of the student production in the

workshop focused on similarities between the forms that could be generated by the grammar for Persian gardens and the grammar for Gropius and/or Breuer's work and the way in which the concept of paradise can be formally translated into architectural design. However, many of the rules borrowed from the two grammars to generate hybrid rules suggest similarities and differences in lifestyle between the two regions and periods. For instance, rules borrowed from the grammar for Persian gardens generate larger rooms than do the rules borrowed from the grammar for Gropius and/or Breuer's work. This difference may relate to a change in family size between the two contexts. In short, the present study, the results from the workshop, in particular, demonstrate the effectiveness of shape grammar as a computational design methodology not only in verifying and describing hybridity in architectural design, but also in generating hybrid and contextual architecture.

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# Cockpit Social Infrastructure

## *Developing a planning support system in Hamburg*

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*In a complex urban scenario with a growing number of stakeholders and high dynamic developments, decision makers rely heavily on public data to make informed decisions. Often though, the available data is heterogeneous and stems from incomplete or inconsistent sources. The planning process, especially the definition of planning goals/needs, is often delayed due to time-consuming data procurement and assessment. This paper describes the development of the Cockpit Social Infrastructure (CoSI), a GIS-based planning support system that serves as an easy-access interface between Hamburgs Urban Data Platform GIS data infrastructure and the municipal planners for social infrastructure, bridging the gap between disciplines and facilitating communication and decision-making between stakeholders. CoSI takes full advantage of the UDP infrastructure and aims to introduce a city-wide tool for planners to conduct holistic, evidence-based planning, grounded in the latest and regularly updated statistical data. The paper outlines the project genesis and underlying technical and administrative structures.*

**Keywords:** *Planning Support System, GIS, Social Infrastructure, Urban Data*

## INTRODUCTION

Planning and maintaining urban systems with regard to the common good is one of the prime objectives in urban planning (cf. APA 1992, Taylor 1998). The Smart City along with growing sharing/service economy sectors and privatization pose great challenges on the practice of urban planning, since vast quantities of data are being generated within urban systems and decentralized private actors compete amongst themselves and with the public sector for their particular interests, challenging the legitimacy and ability of the latter to act (Douay 2018). Within this context the state's role still plays a crucial role in facilitating and managing these more or less self-regulating processes (Lo 2017). To empower municipal planners while coping with the dynamics of a rapidly changing environment, the city of Hamburg launched the development of the Cockpit Social Infrastructure (CoSI), a planning support tool that integrates different data sources and serves as

an easy-access interface to facilitate communication and decision-making between stakeholders (Figure 1). The first part of this paper outlines the theoretical framework for the project's conception; the second part describes the organizational structure of the development process. The third section briefly sketches the technical and functional structure of the tool itself. Finally, in the conclusion, shortcomings and future prospects are critically discussed.

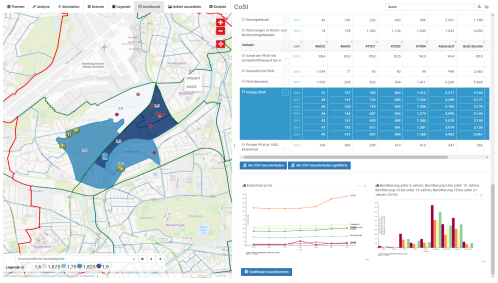

Figure 1
CoSI User Interface

### *Social Infrastructure*

The term infrastructure embodies the background technological networks and systems that support urban life (Latham and Layton 2019). They are comprised of all physical, institutional and human activities that drive the dynamics of cities (Klinenberg 2018, Simone 2004). Access to infrastructure often conditions and is conditioned by socioeconomic factors linked to class divisions. Amongst the multitude of urban systems and networks that shape the patterns and interactions governing the everyday life of all residents, social infrastructure proves to be the prime indicator for social inclusion and livability. Building on Klinenberg (2018), Latham and Layton (2019: 3) summarize social infrastructure as "the networks of spaces, facilities, institutions, and groups that create affordances for social connection." Social infrastructure provides elemental underpinning for intangible dynamics, such as social interaction, education and leisure, and facilitates cooperation and exchange. This fundamental infrastructure is what creates vital communities with high "quality of life", fosters economic vitality (Brown and Barber 2012, citing EDAW and Brittan 2006), and can potentially counteract social divergence and segregation. A strong social infrastructure is needed to create and maintain socially inclusive urban environments allowing for social and political participation regardless of socioeconomic or demographic background (Klinenberg 2018).

Social infrastructure consists of both physical places - such as libraries, playgrounds, schools, hospitals, or public pools - and non- or partly localized services such as elderly care, sports programs, counselling, etc. (Latham and Layton 2019). Although some services can be provided without a specific locality, the accessibility to and coverage of social infrastructure within the urban fabric determine the way some districts perform in terms of social indicators such as unemployment, health, or crime (EDAW and Brittan 2006, Klinenberg 2018, Latham and Layton 2019). "A successful and sustainable local neighborhood is a product of the distances people have to walk to access daily facilities, the presence of a sufficient range of such facilities to support their needs, and places and spaces where a variety of activities can take place." (Llewelyn-Davies 2000).

Since the 1980s and especially after the Digital Revolution, the network of actors and stakeholders providing these kinds of services to people has become increasingly complex. In the context of Germany, social services were primarily established through governmental and religious institutions, as well as cooperative organizations ("Verein", "Vereinswesen"), which are still active nowadays. Over the past decades though, a noticeable share of private providers entered the market, ranging from private schools and non-profit kindergartens to elderly care, private hospitals, and commercial sports centers (Abramovitz and Zelnick 2015). While Abramovitz and Zelnick argue that the shift of social services to a private market leads to a wider range of services, more well fitted solutions, and an increase of efficiency, it could also be argued that it might create a more diffuse field of actors throughout and within ar-

eas, decrease stability of each of the actors, and lead to fluctuations with players entering and leaving the market. With both private and public actors forced into a more entrepreneurial model, public authorities are still key actors when it comes to coordinating and mediating this network of actors, and securing fulfillment of demands throughout urban areas and socio-economic groups (ibid.).

The primary challenge for municipalities is to identify demands and detect lacks of service coverage in time. While wealthy neighborhoods can generally cope with public intervention, there are several examples of poor communities where funding cuts and the failure of providing sufficient infrastructure led to social and economic divergence, migrations, and eventually social crises (cf. Hastings et al. 2015). Uneven responses of communities to services restructure pose a major need to establish a reliable monitoring system that allows public institutions to act swiftly making use of the potentials of digital tools, and Big Data specifically (cf. Douay 2018, Pohlan and Strote 2017).

### *Urban Data Hub / Platform*

Over the past decades in the context of the Smart City, several municipalities and cities have started building up comprehensive data platforms collecting, bundling, joining, and archiving datasets from different sources such as classical census information, geo-referenced mappings, or IoT-devices. Geographic Information Systems (GIS) and their infrastructure driven by open standards (OGC) or commercial solutions (e.g. ESRI ArcGIS) have become an essential asset in urban planning activities (Yeh 2005).

Following that tendency, the city of Hamburg has been building up and extending their Urban Data Platform (UDP) along with the Urban Data Hub (UDH) since 2017, when the latter serves as an organizational and logistical center coordinating all relevant stakeholders and urban institutions that provide their collected data for the former. These projects are an extension of the digital GIS infrastructure that the state Agency for Geo-Information and Surveying (LGV) already provided. The UDH was established as a long-term cooperation between LGV and the CityScienceLab at HafenCity University Hamburg (henceforth referred to as CSL/HCU).

The UDP aims to connect digital systems and services, enabling stakeholders in urban planning processes to cooperate, share logical and analytical capabilities, and to prepare, inform, and assist in decision-making processes. Hereby the UDP follows a decentralized approach only serving as a standardized catalogue and interface for individual data owners' datasets. The city's Digital Strategy 2020 states that the Platform as a city-wide urban data platform is regarded as the city's technological "data hub" whose aim is not a uniform central database, but the standardized technical connection of the various decentralized systems and databases of the city ("System of Systems") (FHH 2020).

### *Decision Support Systems vs. Expert Systems*

When considering application design, stakeholders and developers are tasked with deciding on the appropriate system architecture. With tools designed to aid with problem solving, such as the planning appropriate (social) infrastructure, two design schemas spring to mind: Decision Support Systems (DSS) and Expert Systems (ES) (Table 1). Both are characterized by their capability to provide decision-makers with knowledge and insights aiding them in or steering the decision-making process. Inter alia, they can be distinguished by the type of problem to solve and the relationship between user and application (Turban and Efraim 1986; Edwards 1992). Edwards defines DSS as "[a] system which enables the user to access data and/or models so that he or she may make better decisions", leaving the human user as the one ultimately drawing conclusions based on but not exclusively determined through insights provided by the DSS (Turban and Efraim 1986). ES on the other hand can roughly be described as a system that queries the user for input about the problem (i.e. in spatial planning information about the locality and the

| Attributes | DSS | ES |
|---|---|---|
| Objectives | Assist human decision maker | Replicate a human advisor and replace him/her |
| Wo makes the recommendations (decisions) | The human and/or the system | The system |
| Major orientation | Decision making | Transfer of expertise (human-machine-human) and rendering of advice |
| Major query direction | Human queries the machine | Machine queries the human |
| Nature of support | Personal, groups, and institutional | Personal and groups |
| Data manipulation method | Numerical | Symbolic |
| Characteristics of problem area | Complex, broad | Narrow domain |
| Type of problems treated | Ad-hoc, unique | Repetitive |
| Content of Database | Factual knowledge | Procedual and factual knowledge |
| Reasoning capability | No | Yes, limited |
| Explanation capability | Limited | Yes |

Table 1
Differences ES and DSS (Turban and Watkins 1986)

desired outcome), provides guidance, and calculates solutions based on prior knowledge programmed into the ES itself (Edwards 1992, Turban and Efraim 1986). Calculating appropriate social support programs based on a person's data or suggesting the optimal location for a given building project fall into this category. A closer comparative overview of DSS and ES can also be found in Connell and Powell (1992) and will not be discussed further here.

These categories are not mutually exclusive. Although both usually address different problems and workflows and also require different levels of competency from their user (Edwards 1992) applications often cover problems of both domains. Both early theorists Turban and Efraim (1986) and contemporary authors Liu et al. (2009) argue that an integrated DSS enhanced through ES intelligence can yield better outcomes than either approach independently. Especially the emergence of machine learning (ML) and Big Data opens new perspectives for automated decision making even for complex, non-linear problems (Liu et al. 2009, Demetriou 2018).

As described earlier, urban systems, as they are societal systems, are complex. The multitude of stakeholders and context specific features involved in the urban development process require assessment on a case-by-case basis when it comes to planning processes. Furthermore, the dynamic and diversity of urban development make it harder to establish long-term legislation and guidelines on state or federal level. In Hamburg specifically, this means that when it comes to planning social infrastructure the local district authorities are left with a great degree of freedom on how to achieve the goals set by state legislation. They are under high pressure to estimate demands in time, to react to specific local challenges to coordinate measures with their neighboring districts and are held accountable by both an increasingly active field of non-state actors and the higher governmental levels.

As the considerations above suggest, the urban planning tasks at hand are inherently non- or semi-structured, focusing on unique and changing problems. This paper argues that even given the vast spatial database of UDP and extensive progress in machine learning based problem solving, there are at present no sufficiently established models to automate the multi-dimensional decisions necessary in an urban planning process. To trust ES to provide reliable suggestions and/or rate solutions in complex urban problems autonomously, the underlying models would require intensive testing, evaluation and long-term scientific evidence. This is especially true for the public administration, since it "is legitimate only to the extent it is accountable to the citizenry" (Diakopoulos 2016). With no legislation regulating the evaluation and disclosure of algorithms in governmental use, this poses an uncontrollable risk considering the implementation of an ES planning instrument. In addition, conjuring detailed solutions from an algorithmic black box, particularly when presented as quantitative values (Byers 2011), can create false certainty on the users' side, leaving them unable to evaluate the given result (Zerilli 2019, Bainbridge 1983). Still, as explored above it is to reason that a careful investigation of machine learning

based features within a broader DSS deems promising (cf. Demetriou 2018) and will be discussed in Prospects.

Consequently, the proclaimed goal of a planning support tool is to provide a broad analytical toolbox that is capable of covering a wide range of scenarios and allows the users, i.e. planners, to approacheach case from different angles, run various analyses and represent any stage of a given problem. In other terms: A explorative non-linear decision support system (DSS) that relies on the expertise of its users rather than a linear expert system (ES) providing algorithmically calculated solutions based on a finite set of parameters. Such a DSS emphasizes flexibility and adaptability and is directed more towards knowledge gain of its users than on their data input.

### *Planning Support Systems*

As elaborated, a DSS seeks to provide access to data and information. Hereby DSS can range from data-oriented "File Drawer Systems", merely serving as an access interface to model-oriented "Optimization Models" and "Suggestion Models" (Alter 1980), allowing the user to generate insights beyond the mere retrieval of the respective datasets. As illustrated, UDP and FHH-Atlas already provide the former, enabling the user to visualize any spatial dataset in a GIS environment. Combined with planning-related theory and knowledge as well as instruments and methods tailored specifically to performing a specific planning task (Geertman and Stillwell 2003), such a GIS graphical user interface served by a database is what Batty (1995) and Klostermann (1997) call a Planning Support System (PSS). They contrast the PSS to a Spatial DSS (SDSS), as the former is more directed towards comprehensive urban planning tasks while the latter rather informs decision making on an individual/small business level. As cited by Geertman and Stillwell (2009), Harris and Batty (1993) regard a PSS as a framework combining three sets of components: "the specification of the planning tasks and problems at hand, including the assembly of data; the system models and methods that inform the planning process through analysis, prediction and prescription; and the transformation of basic data into information which, in turn, provides the driving force for modelling and design". In that sense it could be argued, that the Hamburg's FHH-Atlas that already utilizes the data provided by UDP to inform decision making can be considered a PSS.

Geertman and Stillwell (2009) argue that despite the obvious advantages PSS bring, there is a reluctance amongst practitioners to embrace PSS in their everyday workflows. Citing Vonk (2006) they identify 3 types of bottlenecks impeding the adoption of PSS in active practice: a) Instrumental quality b) Diffusion and c) Acceptance. All of these play important roles when considering the slow pace with which public administrations adopt new methodologies and tools in general. For the scope of this work, the focus lay on both the instrument (a) and the user perspective (c). Geertman and Stillwell (2009) sum up that PSS that have been successfully incorporated into the regular workflow outside the research domain worth usually have been requested by the users themselves, addressing straight forward exploratory tasks in contrast to advanced scientific tools that prove unpractical to use and are often user-unfriendly, requiring high levels of involvement and practice. Thus, CoSI has been conceived with the perspective in mind that while sophisticated analytical tools providing all sorts of analytical, modelling and simulation features have been on the market for decades now, but pose virtually insuperable barriers for practitioners. In contrast, the goal was to simplify analytical tasks, visualize the connected data in a readable and tangible way and reflect the actual workflow of planners.

## METHODOLOGY

The methodology deployed in the development and implementation of CoSI is composed by three key stages described below: (1) a prototyping phase outputting an elemental prototype tool used for further development of the system and as basis for discussion, (2) user-story workshops to define the main data sources and functionalities, and (3) a sprint commit-

tee ensuring deployment and evaluating the usage of the tool.

In order to react to the developments discussed in the introduction, the state of Hamburg established the Task Force District Initiative Urban Life ("Quartiersinitiative urbanes Leben", AG QuL) in 2017. According to an official reply issued by the Hamburg senate to a parliamentary inquiry in September 2018, "it is tasked with developing proposals and procedures for the design of neighborhoods that do justice to population growth and increasing diversity and follow socio-spatial guiding orientations. [...] All district offices send representatives from different departments and specialist authorities." (translated from German). In 2018, that committee started exploring the possibility of "developing [...] a digital planning and participation tool as a data basis available to all specialist authorities and district offices" (translated from German) in consultation with the CSL/HCU.

As illustrated above, the required tool should be tailored to the needs of a diverse field of experts from different specialist authorities. Its structure should accommodate their workflow and provide them with insights and knowledge without predetermine the outcomes. Based on a prototype developed by CSL/HCU in the context of UDH the state councilors decided in June 2018 to develop the tool until it was ready for use for a broad application in the Hamburg administration. In order to maximize acceptance amongst the estimated users, the state contracted a consortium of LGV and CSL/HCU for a multi-stage development accompanied by scientific evaluation.

In contrast to the still predominantly rigid practice in software projects within the public administration, the process should follow Agile methods, providing the client with quick adaptation and frequent value delivery (Mergel 2018, Torrecilla-Salinas et al. 2013). Mergel (2018) gives a broad overview of potentials to Agile methods in governmental projects. Due to the project's construction with a relatively small development team of three in comparison to a vocal and active stakeholder group of 15 planning experts with changing composition, the team of CSL/HCU-LGV opted not to follow one methodology strictly but constructed a framework based on SCRUM (cf. Schwaber 1995). The main difference lies in the roles assigned to the stakeholder group and the developers. The stakeholders as expert planners from within the public administration and the developers of CSL/HCU with a dual background in software development and urban planning research were set up in a dialogue, each providing their expertise and proposing features and development directions independently of the product owner, who acted in a more coordinating fashion. That construct proved quite successful as will be discussed below.

### *Prototyping*

With the researchers from the CSL/HCU having expert knowledge concerning the structure and the capabilities of GIS based decision support tools, it was necessary to establish a common ground with the rest of the stakeholders to start the work and thought process. For this purpose, a prototype was developed, that was aimed at the illustration of the basic layout and functionality of CoSI on the base of a real-world example. The district of Hamburg Nord chose the neighborhood of Groß-Borstel as the prototype location. With the work on a rather big construction site starting in the near future, it was supposed to illustrate the vast changes that social infrastructure faces in times of changing physical infrastructure and demographics. The questions in this particular setting focused especially on kindergarten infrastructure. A static calculation was programmed, that showed the changing number of available kindergarten places per inhabitant below the age of six before the housing project and after its completion. The prototype was shown to a wide range of audiences including the immanent stakeholders and fulfilled its role of clarifying the CoSI vision. The working prototype was used as an example and basis for a qualified discussion amongst the stakeholders, providing visual aid for communicating ideas both ways.

### *User Story Workshops*

As typical for Agile methods, user story workshops were held with the AG QuL and other volunteers from different specialist authorities throughout the city to identify the initial development goals (Figure 2). Originally, these groups consisted of experts from the departments for 1) Social services, labor, families and integration, 2) Health and customer protection, 3) Housing and urban development, 4) Internal affairs and sports, 5) Finance. Thus, covering a broad range of topics, the workshops sought to first identify a) the most pressing, recurring themes in planning, b) the planners' traditional workflow and c) the data and/or data correlations needed/desired. The results were structured in a matrix mapping functionality over topics, trying to find and weigh the most requested features and data.

Figure 2
CoSI User Story Workshop with interactive table

At the present stage, two workshops were held: One at the beginning of the concept phase in summer 2018 and one in summer 2019, prior to the official development start, aiming at rollout of a pilot in February 2020. Where the first workshop conducted in advent of developing the prototype indicated a focus on the kindergarten and after school care that presumably mostly stemmed from the acute demand in Groß-Borstel, a change in stakeholder group composition and possibly also the experience with the prototype led to a shift towards sports, youth centers and leisure. Due to the well-received pilot and the agreed-upon continuation of the project (see Prospects), further workshops in similar setups will be conducted in 2020/21 to extend and refine CoSI's scope and design.

### *CoSI Sprint Committee*

Following the contract laying out the road map and second user story workshop in August 2019, the CoSI Sprint Committee ("Arbeitsgemeinschaft CoSI Sprint") was established through the Hamburg senate's project management. That committee mostly consists of the experts previously involved in AG QuL and additional specialist officers invited to accompany the process. As introduced the committee forms the key strategy element to ensuring acceptance for the application and a product tailored as closely as possible to the requirements of active planning practice. Also, the stakeholders would receive a stage version of the latest development state, providing continuously user testing that was gathered and evaluated to be incorporated and informing a qualified exchange.

In biweekly reviews the development team would present the state of development to the group and discuss further steps and adjustments. Hereby these sessions were structured into three main segments: a) Reviewing the users' experience with the stage environment and the latest sprint results, b) discussing functional requirements and introducing prototypical ideas for future developments and c) discussing data requirements and data procurement to be passed on to the UDH and the relevant departments. Based on the matrix developed through the user story workshops, that parallel stream of data and functional topics proved to be efficient in that it allowed for rapid prototyping and development of functionality based on already established data and extending these features to data streams incorporated throughout the process.

## RESULTS

Technically, the CoSI application was developed as a pure front-end application based on web technology as a separate, specific portal on basis of the aforementioned Masterportal. This means that the application is completely independent of the data basis described above and runs on the computer of the respective user in the browser, just like a normal

website a Web-GIS. In the case of CoSI, this website is hosted, as is the UDP and the FHH-Atlas, on the servers of the LGV. As it is still in piloting phase and legal considerations are not concluded as of today it can only be accessed on the intranet of the Hamburg administration. In practice, CoSI in its existing form could be deployed on any web server and made publicly accessible. Although, as explained, some sensitive datasets are not available on the internet, that would not compromise CoSI's core functionality.

While CoSI itself was primarily intended as a visualization tool in its conception and prototype phase, it has increasingly developed into a complex analysis and planning application over the course of the project period. At CoSI's core lies the layering of regularly updated statistical characteristics of the administrative areas, which are supplied by the State Statistical Office (StaLA), and various specialist data from the various authorities. Based on queries taken from the user story workshops it provides the planners with a number of analysis functions to identify sociodemographic relationships, to recognize trends and to determine relationships between the existing infrastructure offering and the relevant target groups. Through accessibility and network analyses, the tool helps to find suitable locations and potentials for infrastructure development. The results of these analyses can be visualized directly from CoSI and used as a basis for decision-making and discussion. The workflow follows a three-step logic from the visualization of data, the analysis, i.e. the contextual linking of information, to the simulation of the effects of potential measures.

In January 2020, the first development phase concluded with CoSI entering a piloting period until end of May 2020. During that period, it is available to all departments in the borough of Hamburg-Nord who the project management addressed as active and potential participants in the design process to ensure high acceptance and instrumental quality. An evaluation process will accompany this phase gathering feedback and input that will be incorporated future design, monitored by the sprint committee. As of writing of this paper, the continuation has been confirmed through the administration with citywide rollout in 2021.

## DISCUSSION AND CONCLUSION

At its present stage, CoSI can be regarded as a valuable PSS aiding the every-day practice of public urban planners. Without being able to draw conclusions from extensive evaluation, user testing and real-world field tests, the authors can state that CoSI was well received by the stakeholders involved and the scientific and public audience who appreciate its accessibility for exploratory uses so far. Furthermore, the process proved efficient and inclusive, striking a balance between the demands of the planners and the requirements of the political decision makers.

One of the reasons that make CoSI differ from other software projects in public administration is its unique composition with a diversity of different stakeholders. The senate, the planners of social infrastructure with a multitude of professional backgrounds, the LGV and the CityScienceLab composed the team that made CoSI what it is today. The authors hope that it can serve as a lighthouse project of how urban data can and should be utilized, how tools shall be developed in a collaborative methodology and how a project with a narrow thematic focus can have a wide-ranging impact on the urban data landscape of a city. Through the process of dialogue, a large set of new data sources was introduced to the UDP and agencies, that initially were not keen on partaking and providing data, were convinced of the necessity to collaborate in CoSI and hopefully with the UDH in future projects.

One pitfall of the project is the still existing concerns about the opening of such a platform to the general public. There is a strong reluctance within a number of departments in the City of Hamburg of giving the citizens access to this analytical tool, since they reasonably fear to be overwhelmed with requests and inquiries. In consideration of necessary concerns about the privacy of certain datasets and an open discussion about the limits and risks of partic-

ipation and community design, citizens and the actors of the civil society should be able to analyze data that is subject to Hamburg's transparency law and let their political demands be influenced by a realistic assessment of the current social reality. The authors see valuable potential in opening a two-way communication between administration and citizenry, allowing the planners to draw from public knowledge and even allowing the public to negotiate decisions in a decentralized fashion themselves (cf. Douay 2018, Geertman and Stillwell 2003). In times of widespread political disenchantment, the claimed commitment to open data and the possibility of fast spreading, making tools like this public seems to be inevitable.

### *Prospects*

Already during the conception and development phases features were drafted that could not be incorporated in the pilot. The decisions were made for a) reasons of prioritization as outcomes of the user story workshops and b) to limit the tools initial scope to a tangible, user-friendly workflow.Further development should be directed towards the following:

Additional potential extensions are given here:

1. Incorporating new/additional data sets from the UDH processes into existing functionality
2. Simulating planning decisions and their impact on supply/demand
3. Extending the accessibility analysis through real-time data and Agent Based Modelling
4. Rethinking the system architecture away from a frontend-based application to a series of backend modules.
5. Extending workflow and persistence by adding savable work-sessions, network collaboration and a presentation / workshop mode for communication of results
6. Integrating CoSI with other PSS / GIS applications, e.g. *LIG Location Finder* (Public Real Estate Agency, Landesbetrieb für Immobilienmanagement und Grundvermögen Hamburg), currently under development at CityScienceLab, HCU Hamburg, *GRACIO*, a simulation tool for masterplan performance in the competition phase, currently under development at CityScienceLab, HCU Hamburg, *DIPAS* (Digital Participation System Hamburg), Hamburg's tool for participatory processes and citizen involvement, developed by LGV, based on Masterportal (Lieven, 2017)

As a first result of the evaluation with users and political decision makers, a priority topic for the further development should be simulation and prognosis. Although these are complex computational problems hinting at the issues explored in DDS vs. ES and touching a plethora of unresolved design questions, they can provide significant benefits. In particular, simulations can allow the user to reason about hard to intuit future implications of certain decisions and to consider possible alternatives where force of habit might shroud unconventional ideas.

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# Application of Robotic Technologies for the Fabrication Of Traditional Chinese Timber Joints

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*The traditional Chinese building design was influenced by the climate and the sociogeographical conditions of the different regions in China. They were usually constructed out of wood relying on timber-joint based construction systems. Amongst the wide variety of the structural elements, the Dougong (bucket arch) is one of the most common components of traditional wooden framework buildings, presenting a high level of complexity. Parametric design and robotic technology enable new possibilities regarding its fabrication and application in contemporary architecture. Our paper will explore how the Dougong components could be reinvented through the use of parametric tools and robotic fabrication methods and thus applied to contemporary architectural structures. We will analyse and compare the properties of the original Dougong with the reinvented unit by using finite element analysis and digital optimization tools. Our findings will provide an insight into the traditional construction principles of the joint and how these can inform a design and fabrication framework for its application in contemporary buildings.*

**Keywords:** *Dougong joint, timber structures, parametric design, robotic fabrication, optimization algorithm*

## INTRODUCTION

### *A brief history of the Dougong joint*

The Dougong bucket arch is an independent category, withing the traditional Chinese timber framework systems. It consists of many different types of Dou (square load-bearing member) and Gong (arch load-bearing member), (Liang, 2005). During the Qing dynasty, there were even specialised Dougong making craftsmen, called Dougong carpenters (Pan, 2011).

Historically, the main structure of traditional Chinese buildings is a load-bearing timber framework while the walls are part of the building. The roof's structural load is transferred from the beam purlin to the pillar into the structural system. There is a complex component named Dougong, which is a transition component between the beam purlin and the pillar. It has been a unique element of Chinese architecture for thousands of years. (Liang, 1985)

The earliest Dou appeared during the bronze age of the Shang and Zhou Dynasties, and the appear-

ance of Gong followed later (Pan, 2011). According to Yang Hongxun's 'Architectural Archaeology Study of Tomb Buildings, Murals and Burial Artefacts, the structure of Dougong had been widely used and achieved its mature stage since the Han dynasty, 206 BC-220 AD, (Liu, 1982).

The proportions and the name of the Dougong components before the Song Dynasty (960-1279) are difficult to retrieve since there are not related sources to refer to. However, two important historic rulebooks the Yin Zhao Fa Shi and the Gongchen Zuofa Zeli provide both standards and structural regulations for buildings and building components. The first was completed by Li Jie in the Song Dynasty (960-1279) while the second was published by the Ministry of Construction of the Qing Dynasty in 1734. In this paper, we mainly focus on studying the Dougong developed during the Qing dynasty (1636-1911) as a large number of buildings from this period have been preserved and can provide a reliable database for analysis.

### *Dougong types*

The size, the structure, the technology and the materials of at least thirty different Dougong joints are recorded in the historic rulebook Gongchen Zuofa Zeli. They can be classified based on their function and position inside the building (Ma, 2003). A first classification can be obtained by dividing the Dugong into two main categories according to its position: a Dougong located in the extension of the building is called 'the external eave Dougong' and the one located inside the eaves is called 'the inner eave Dougong'. Furthermore, the external eave Dougong can be divided into an intermediate set, a column set and corner set (Ma, 2003). This paper will mainly focus on the external eave Dougong, and particularly the intermediate set (Figure 1).

Figure 1
Principal parts of a Chinese timber-frame building. (Drawn by the 'Society for Research in Chinese Architecture')

### *Dougong components*

The Dougong balances the weight of the roof and transfers its loads from the roof to the pillars. Traditionally it was built manually, requiring a significant amount of time for its completion. It is composed of five different components (Figure 2), which include: the Gong, Qiao, Ang, Dou, and Sheng, (Liang 2006).

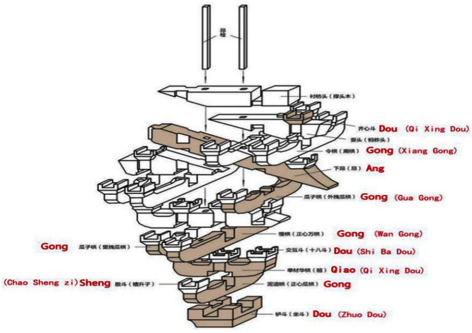



Figure 2
Components' of the Dougong

In modern years the ancient knowledge and applications of the Dougong are disappearing. We are confident that parametric design tools and robotic fabrication techniques could be used for the reinvention of the joint and ensure its survival into the modern era. In particular, our research will try to answer the following questions:

1. How can we simplify the Dougong elements by using parametric modelling tools and robotic fabrication techniques?

2. How could a reinvented joint be applied in contemporary architecture?

To achieve this we will start by studying different cases studies which have applied robotic technology to reproduce wooden joints. We will then propose a framework which will integrate the traditional construction and design principles embedded in the Dougong and will allow us to reinvent the ancient joint.

## RESEARCH CONTEXT AND LITERATURE

Digitalisation and robotic reproduction of elements of a Japanese traditional timber system are being described by Takabayashi et al. (2018). In their experiment, the Japanese team introduced a novel method for the robotic reproducing a roof corner detail of a Japanese pagoda by using five tools; a circular saw, a square chisel, a vibration chisel, a router and a five axes KUKA KR 6R 700 robotic arm to reproduce the different joint components. The robotic toolpath was generated by a specifically developed CAM programme. As Japanese timber systems are based on Chinese systems, this method provides valuable insights into designing and creating Chinese joints too. However, this study does not attempt to reinvent the traditional elements, neither examines their application on modern-day design driven by robotic technology and parametric design tools.

The research team led by Mikayla and Kevin (2018) investigated the use of parametric tools and robotic technology to reproduce traditional joints, suitable for contemporary architectural applications. They employed a 6-axis ABB IRB 6700 robotic arm and the HAL Grasshopper plug-in, to produce a set of physical prototypes using mortise splices and curved splices in their attempt to explore possible new joints. As a starting point, the researchers fabricated a simple physical model by using a CNC mill to identify possible deficiencies. The data from that first experiment helped them to identify and resolve issues before proceeding with the robotic fabrication.

The research team led by Böhme explored the potential of applying robotic fabrication for the reconstruct a historical joint employing parametric tools and a KUKA KR125/2 and Agilus KR6 R900 Sixx robotic arms. The experiment's findings suggested that the process can be successful without modifying the joint's geometry.

The team led by Yuan Feng explored how to use a 5 axis CNC router to design and fabricate a structural installation based on a traditional Chinese eaves rafter. Firstly, they analyzed the bending moments of the joint by using the Grasshopper plugin Millipede. After finding out about the underlying structural principles, they designed an umbrella-shaped structural installation by using a unit based on the traditional rafter proportions. In the structural simulation stage, the topology function was applied to optimize the dimensions of the unit before proceeding with its robotic fabrication.

Chai and Yuan, (2018) fabricated a complex wooden pavilion at the University of Tongji, using a gantry robotic system and the Grasshopper plugin Karamba3D, as well as a KUKA R2700 robotic arm. They developed a band-saw end-effector and applied it to fabricate curved wooden beams and mortise-tenon joints. The experiment proves that robotic arms can fabricate complex wooden structures with their band-saw end-effector more efficiently and accurately than with a CNC mill.

Finally, in a case study conducted at the University of Sydney (Mitchell, 2017), Dove, an open-source software plugin was used for developing a 3D model of a timber joint. The physical prototype was fabricated by a KUKA KR60 6-axis robot and a milling spindle end-effector. They have also developed a tool, which is reducing milling time, simplifying the too paths and saves material.

All the projects presented here are investigating how to reproduce building components or building parts by employing robotic technology based on the proportions of the original structure. In contrast, our work will focus on how we could re-invent the Dougong joint, thus to apply it in contemporary design solutions.

## METHODOLOGY

Our research method consists of a design experiment and its validation via digital simulation and physical prototyping. In particular, our method includes four main phases and a feedback loop.

In phase one we will analyse the Dougong's components and proportions, based on sources referring to the Qing dynasty, where the Doukou system (bucket mouth system) is used as a standard unit for each building module. This system is an optimised version of the Caifen system, which was developed during the Song dynasty.

In the second phase, we will simplify the joint and develop a digital, parametric modelling framework of a novel design unit, with references to the proportions and the structural properties of the traditional Dougong as well further geometrical properties allowing it to be robotically fabricated.

Phase three includes the structural simulation and optimisation of the design unit. We will test both a linear and a non-linear structure using the Millipede plug-in for Grasshopper. Phase three will also include a robotic fabrication simulation using the firmware RoboDK and Grasshopper. A feedback loop to face two is included here, making sure that all simulation results will feedback into the original design starting point. Finally, in phase four, which will not be included in this paper, we will proceed to the validation of or design framework via a physical prototype using a CNC mill and UR 10 robotic arm. The CNC milled prototype will help us to optimize the fabrication process, prior to its final fabrication destination, the UR10 robotic arm. That will also include the development of the appropriate end-effectors. This paper will cover the proportion and mechanical properties study of Dougong, the design methods of the unit, the assembly possibility of the unit, and the simulation and optimization of the unit in Millipede (Figure 3).

## DESIGN EXPERIMENT

As previously described, our design experiment consists of the analysis of the traditional Dougong proportions and design rules, as well as the parametrisation of a novel design unit. Firstly, we will study Dougong's proportions by reviewing the two rule books mentioned previously. We will then design the unit according to the mechanical properties as described by Yuan (2012), using the proportions and connection methods as recorded in the books Qishi Yin Zhao Zeli (Liang, 2006) and Gong Chen Zuo Fa (Liang, 2006) and the Chinese ancient archi-

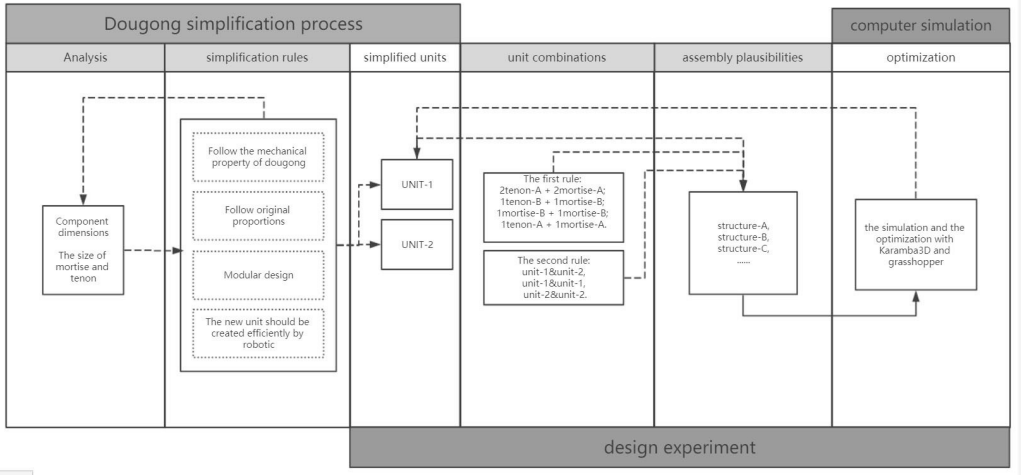



Figure 3
Research methodology framework

Table 1
The sizes and proportions of the intermediate set ( the red part has been used in the paper)

| Rule table of the intermediate set (unit: Dou) | | | |
|---|---|---|---|
| ***Component name*** | ***Length*** | ***Width*** | ***Height*** |
| base block(大斗) | 3 | 3 | 2 |
| **the first transverse bracket arm(单翘)** | **7.1** | **1** | **2** |
| the second transverse bracket arm(重翘) | 13.1 | 1 | 2 |
| **axial oval arm（正心瓜拱）** | **6.2** | **1.24** | **2** |
| axial long arm（正心万拱） | 9.2 | 1.24 | 2 |
| the first cantilever arm（first-ang）（头昂） | base on the kind of dougong | 1 | ahead 3, back 2 |
| the second cantilever arm（second-ang）（二昂） | base on the kind of dougong | 1 | ahead 3, back 2 |
| the third cantilever arm（third-ang）（三昂） | base on the kind of dougong | 1 | ahead 3, back 2 |
| tail end of *grasshopper headwith sharp poinyed cutout treatment*（shua-tou）（耍头） | base on the kind of dougong | 1 | 2 |
| uppermost piece parallel to *ang* or *qiao* with hempleaf shaped end（撑头木） | base on the kind of Dougong | 1 | 2 |
| outward and inward oval arms（单才瓜拱） | 6.2 | 1 | 1.4 |
| outward and inward long arms（单才万拱） | 9.2 | 1 | 1.4 |
| outward and inward regular arms（厢拱） | 7.2 | 1 | 1.4 |
| purlin socket piece（桁碗） | base on the kind of Dougong | 1 | base on the kind of Dougong |
| connection block（十八斗） | 1.8 | 1.48 | 1 |
| small block（三才升） | 1.3or1.4 | 1.48 | 1 |
| center block（曹升） | 1.3or1.4 | 1.72 | 1 |

tecture woodwork construction technology manual (Ma, Bingjian. 2003). In parallel, other parameters contributing to the efficient robotic fabrication of the unit and its clusters will be applied.

## *Analysis*

There are eleven classes in the Doukou system . The width of the first-class Dou is 19.2cm, thus the width of one Doukou is 19.2cm. Each class is linked to a particular building function and any change from class to class is based on the formula:

1 Dou = 19.2cm + (11- N) * 0.5 Cun, (1Cun=3.33cm), N: the class of Cai (1, 2, 3, 4, ..., 11); Cun is the traditional unit of length in China.

We will use the table and the formula to design all components for our design experiment. The intermediate set will be explored firstly, as described by Ma (2003) in table 1. The distance of the main stress points is 3 Dou according to the proportion analysis of the Dougong components (Table 1). The connection method of the components is based on the principle of mortise and tenon. A tenon is usually located between two stress points. Two stress points are connected with a mortise. One Dougong element is composed of at least one tenon and two mortises.

## *Parametric design framework of novel design unit*

The new unit should respect the proportions and the structural properties of the traditional Dougong allowing the unit to be fabricated by a robotic arm. A way to do that is by minimizing it to the way the components are being connected as well as its mechanical properties as demonstrated in figure 4, (Yuan et al. 2012). We have chosen the second layer of an interlocked bracket set including the first transverse bracket arm and the axial oval arm as shown in Table 1. The length, the width and the height of the two elements are adjusted to integers, the decorative elements and the complex curve can be removed aiming to improve the effectiveness of its robotic fabrication (Table 2).

Table 2
Sizes and proportions of unit 1 and unit 2

| Rule table of Unit 1 and Unit 2(unit: Dou) | | | | |
|---|---|---|---|---|
| ***component name*** | | ***length*** | ***width*** | ***height*** |
| connect ways | tenon.A | 0.5 | 0.5 | 0.5 |
| | tenon.B | 1 | 1 | 0.5 |
| | mortise.A | 0.5 | 0.5 | 0.5 |
| | mortise.B | 0.5 | 0.5 | 0.5 |
| Unit 1 | | 6 | 1 | 2 |
| Unit 2 | | 6 | 1 | 2 |

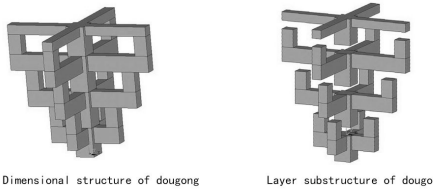



Figure 4
Simplified structure model of Dougong (Yuan, 2012)

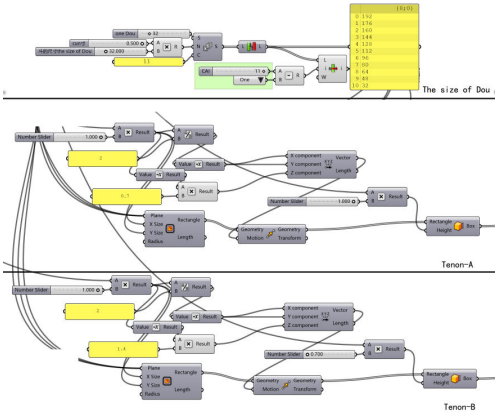



Figure 5
The parametric models visual code for unit 1 and unit 2

We have parametrized the two main Dougong units in Grasshopper (Figure 6). The units are composed of four elements: tenon A, tenon B, mortise A and mortise B (Figure 5).

There are three main rules of connection possibilities (Table 3): unit 1 & unit 2, unit 1 & unit 1 and unit 2 & unit 2. Furthermore, every connection type includes three different unit groups: the square-shape (P1, P2, and P3), the T-shape (P1.1, P2.1, and P3.1), the cross-shape ( P1.2, P2.2, P3.2) and L-shape( P1.3, P2.3, and P3.3) respectively, which is the basic shape of the assembly (Figure 7). According to these rules, the combination of different units will produce different results of assembly. In this study, we are assessing seven design units, A, B, C, D, E, F and G (Figure 8). The key element of structure A is P1.2 (possibility1.3), and the key elements of structure B are P1, P1.2, and P3.3. The connection method of the two structures is P2.2 and P3.2. P1.1 is applied in structure C as the key element. Structure D consists of the P3.3 unit, the structure E consists of the P3, P2 and P1.2 units, and the structures F and G consist of the P1.2 unit.

The structure was developed by two basic rules: Rule one is based on the combinations of unit 1 & unit 2, unit 1 & unit 1 and unit 2 & unit 2. Rule two is based on the combinations of 2 tenon A + 2 mortise A; 1 tenon B + 1 mortise B; 1 mortise B + 1 mortise B; 1 tenon A + 1 mortise A. The & symbol indicates the combination of two units. For example, unit 1 & unit 2 means one element consists of unit 1 and unit 2. The '+' symbol indicates the connection method of two units. For example, 2 tenon A + 2 mortise A means that the two tenon A of one unit connects with the two mortise A of another one unit.

## SIMULATION AND OPTIMIZATION

The optimization and simulation process consists of two parts. The first part includes the comparison of the mechanical properties of the original Dougong with those of the new unit by using the plugin Millipede. The second part focuses on optimizing the cross-section of the new unit employing a genetic algorithm by using the Galapagos plugin for Grasshopper. The max-deflection of the structure will be minimized after optimization, which will enhance its stiffness. We chose to analyse and optimize the P1.2 joint, as it is very similar to the original Dougong. The new unit is built based on the first Cai level, equal to one Dou (19.2 cm) x 1.5 Dou (28.8cm) x 6 Dou (115.2cm).

The optimisation of the joint is focusing on the values of three main parameters: the Young's Mod-

| RULE | *2tenon.A + 2mortise.A* | *1mortise.B + 1mortise.B* | *1tenon.A+ 1mortise.A* | *1tenon.B + 1 mortise .B* |
|---|---|---|---|---|
| ***unit-1&unit-2*** | P1(possibility1) | P1.1(possibility1.1) | P1.2(possibility1.2) | P1.3(possibility1.3) |
| ***unit-1&unit-1*** | P2(possibility2) | P2.1(possibility2.1) | P2.2(possibility2.2) | P2.3(possibility2.3) |
| ***unit-2&unit-2*** | P3(possibility3) | P3.1(possibility3.1) | P3.2(possibility3.2) | P3.3(possibility3.3) |

Table 3
The rules of assembly

Figure 6
Tenon and mortise elements for Unit1 ( left ) and Unit2 ( right)

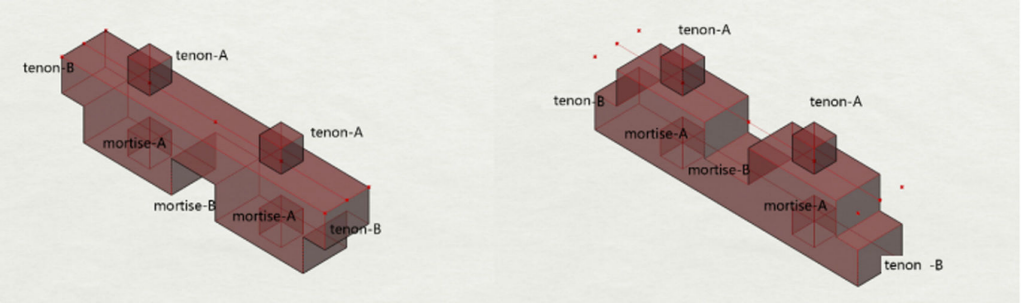
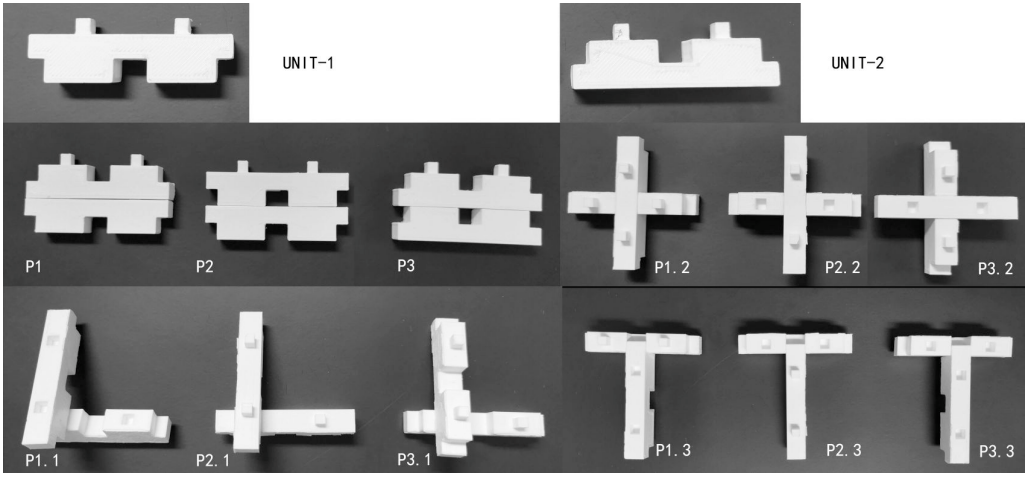
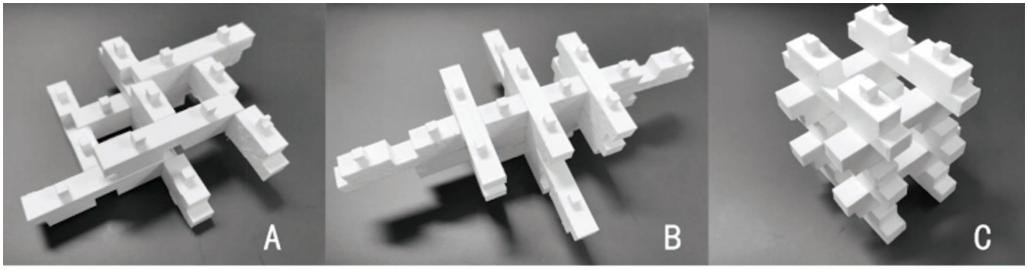



Figure 7
The re-invented rules of assembly

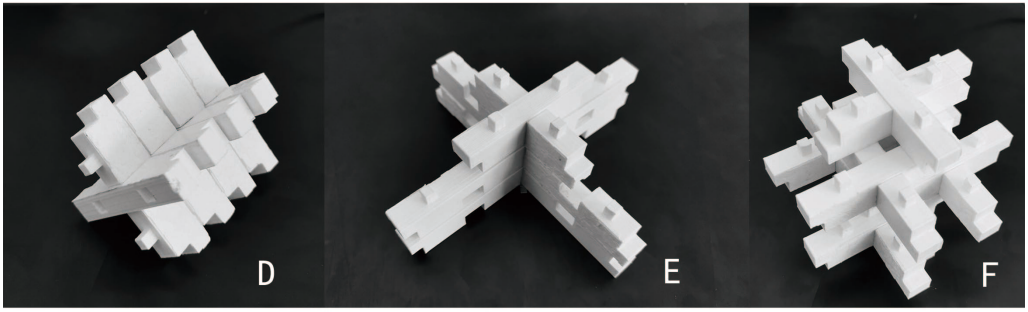



ulus, the Poisson's ratio and the mass density. The Young's Modulus is used to measure the stiffness of solid materials, while the Poisson's ratio describes the contraction of a material in the direction of loading. We will compare the displacement on 4 points on the z-axis of the two structures (Figure 9). We are assuming that the structures are subjected to a uniform load of 1000 N/mˆ2. According to the Millipede analysis results, the displacement of the four points on the original Dougong is 1.04e-6 m, 1.21e-6 m, 1.08e-6 m, and 9.92e-7 m. The displacement of the points on the P1.2 joint is 1.06e-6 m, 1.25e-6 m, 1.10e-6 m and 1.08e-6 m. The difference between the displacement of the four points is only 0.02e-6 m, 0.04e-6m, 0.02e-6m, and 0.08e-6m, which proves that the mechanical properties of the original Dougong and the new unit are similar.

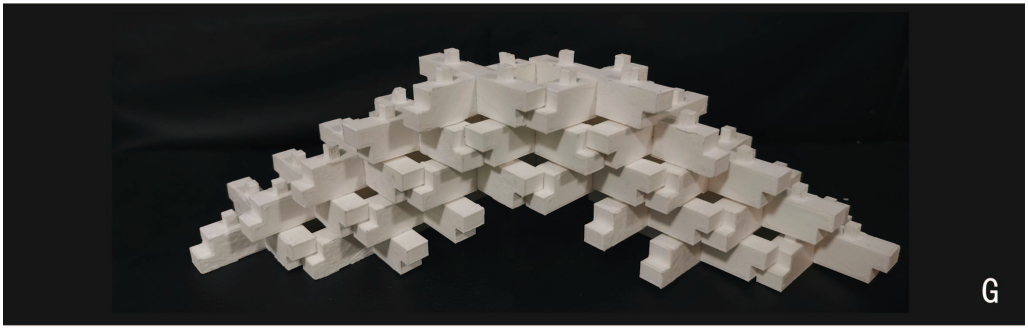
The second part focuses on optimizing the cross-section of the new unit by using the Galapagos plugin for Grasshopper. We chose the P1.2 joint, as the object of the analysis due to its similarity to the original Dougong. We have used the same property values as in the previous simulation. The max-deflection of the structure is 1.375e-6m and 1.055e-6 m before




Structure-A: (P2.3) +(P2.3)  Structure-B: (P1) + (P1.2) + (P3.3)  Structure-C: P1.1




Structure-D: P3.2  Structure-E: (P3)+(P2)+(P1.2)  Structure-F: P1.2




Structure-G: P1.2

Figure 8
The different assembly possibilities of the reinvented Dougong elements

and after optimization. The new width and height of the cross-sections of the two units are 1.12 Dou (21.5cm) and 1 Dou (19.2cm), (Figure 10). The volume of one unit is 0.051 m^3 and 0.038 m^3 before and after optimization.

Figure 9
The four points used on the displacement analysis

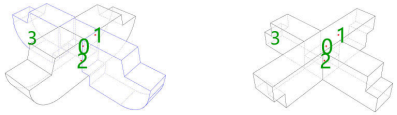
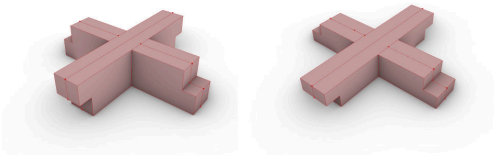



Figure 10
The digital model of the P1.2 joint (left) before optimization and the model (right) after optimization in Millipede



## DISCUSSION AND CONCLUSION

The paper is exploring a strategy for simplifying the elements of Dougong to make it more suitable for contemporary architectural applications. According to the mechanical properties and proportions of the Dougong, we simplified two elements of the interlocking bracket set via adjusting the dimensions to integers and removing the decorative elements and the complex curves. Furthermore, we designed two units and defined two rules of connecting the units based on the original connection of Dougong. The inter-combination of the unit will form different assembly possibilities following the described rules. We have explored seven assembly possibilities and simulated a connection structure in the Millipede. The cross-section of the unit was optimized to be 1.12 Dou in width, 1 Dou in height.

After analysing the results we have concluded to the following: firstly, the displacement differences between the points of the original Dougong and the connection P1.2 are only 0.02e-6 m, 0.04e-6m, 0.02e-6m, and 0.08e-6m, which proves that the properties of the two structures are similar, thus our design method is feasible. The volumes of the two structures are 0.157m^3 and 0.102m^3, which means that the material usage of the new unit is less than the one in the original Dougong. Secondly, when the cross-sectional size of the new unit is 1 Dou in height and 1.11 Dou in width, the volume of the structure P1.2 should be 0.076 m^3 according to the optimization. However, the volume value before the optimization was 0.102 m^3. The difference is 0.026 m^3, which means that the material usage of the unit could be reduced. At the same time, the difference between the max-deflection of the structure is 3.2e-7m, which means that the property of the structure is enhanced. Overall, it becomes evident that the simplified and optimized joint has the potential to be integrated into design solutions, as it does not only have a very similar structure and mechanical properties with the original joint but also has a simpler shape and uses less material.

However, as we currently only focused on the intermediate Dougong set, we will continue applying this method to design a new unit based on the study of the set on the column and the corner set, and finally, make a data table to facilitate the robotic process of the wood unit. We will also explore the specific use of these structures on modern designs, such as the structure of the bridge and the structure of the pavilion, all of which need to be completed in cooperation with robot technology and Millipede.

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Figure 4: Yuan, JL, Shi, Y, Chen, W and Wang, J 2012, 'Finite element model of Dou-Gong based on energy dissipation by friction-shear', Journal of Building Structures, 06, p. 33.

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# Liquid Stereotomy - the Tamandua Vault

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*A renewed interest in stereotomy, narrowly entwined with digital technologies, has allowed for the recovery and proposal of new techniques and expressions in this building approach. A new classification scheme for stereotomy research allows for the framing of various aspects related to this discipline, including a newly developed fabrication system specially tailored for the wedge-shaped voussoirs. This fabrication system is based in a reusable mould which may assume an infinite number of geometries, avoiding the wasteful discarding of material found in subtractive strategies. The usage of a mould also allows for more sustainable materials to be employed, catering to current challenges. The strategies subject for demonstration in this project rely on various bottom-up approaches, which involve particle physic simulations such as a hanging model to compute an optimal stereo-funicular shape, or spring mechanisms to find optimal coplanar solutions. The proposed mechanisms work in a parametric algorithmically environment, able to handle dozens of uniquely different voussoirs at the same time. Together with the automatic translation to fabrication data, the proposed shape complexity would hardly be built with classic tools. The Tamandua Vault project has the purpose of exemplifying the possibilities of an updated stereotomy, while its design demonstrates current strategies that may be employed in the resolution of complex geometrical problems and bespoke fabrication of construction components for stereotomy.*

**Keywords:** *stereotomy, digital design, digital fabrication, compression, sustainability*

## INTRODUCTION

A great array of the most admired historic buildings found in Europe are built of precisely cut stone. The discipline which allowed for the precision and materialisation of these lithic geometrized blocks is stereotomy, a name which originates in the words, from the greek, στερεο'ς, stereo, solid and τομή', tomia, section (Fallacara 2014). Initially known as Coupe des Pierres, stereotomic knowledge was disseminated in a large number of treatises allowing for architects to gain an important independence from stonemasons, contributing decisively to the creation of the renaissance ideal of the architect role. Stone construction, together with its brick counterpart, dominated the building techniques until the introduction of new materials and processes brought

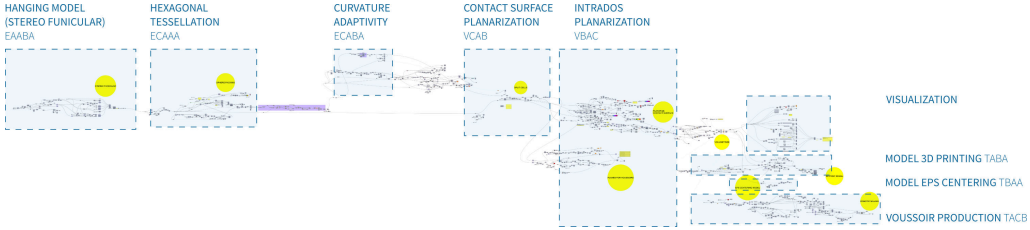



Figure 1
Global view of the algorithm created in Rhino Grasshopper with the various stages labelled in blue.

by the Industrial Revolution. These novelties, epitomised by steel and reinforced concrete, present the possibility of building larger spans with lower rises, allied to the lowered cost factor due to standardisation and mass production. The art of building stone arches and vaults to cover spaces became a rare exception in a world covered in steel, be it in the form of metallic profiles or reinforced concrete.

Despite falling out of favor, qualities inherent to stereotomic construction are still - or even more - valid today, namely: prefabrication; dismantling and rebuilding; usage of local materials; bigger lifespan and acoustic and aesthetic qualities, among others. Recent researches have resurfaced the interest in stereotomy, which has become more interesting due to the possibilities brought by new digital technologies. From the digitalisation of stereotomic techniques (Fallacara 2003), passing on to a reinterpretation of design and fabrication processes (Rippmann et al. 2016), stereotomy is being experimented with a variety design and building approaches, as well as different materials, calling for a reinvention of the discipline, called Stereotomy 2.0 by Fallacara (2018).

The large amount of directions in which experiments and actual constructions are being tested (e.g. materiality of the voussoir, fabrication technique, stability principles, joint geometry, centering technique, among others) is highly disruptive of the great source of knowledge on stereotomy: the classic treatises like those of de l'Orme (1567) or Frézier (1738). In an attempt to bridge this apparent gap, the author has published a draft for an Expanded Semantics of Stereotomy (Azambuja Varela 2019) in which a wide range of concepts related to stereotomic design and construction are classified in an ordered structure with a clear naming convention, which will be used in this article. One of the possibilities of innovation in stereotomy is in the voussoir fabrication field, where masons hand labour is being replaced by automated machinery. The author has researched in a moulding process in which very limited waste is generated with the production of bespoke multiple varied geometry blocks (Azambuja Varela 2017, 2018), reducing machining time and widening the array of possible materials to be employed in a stereotomic construction. This novel materialisation system for voussoir production reached satisfactory results in the form of a variable mould system, which was used to produce a variety of voussoirs for four prototypes whose main purpose was to validate that specific research agenda. This moulding system will be put to test in the following project, whose goal is to validate a complete flow for stereotomic design under the paradigms announced in this work, using digital-based strategies without which its design and construction would be very difficult to the point of not being a feasible endeavor.

## DESIGN

The Tamandua Vault project has the purpose of exemplifying the possibilities of an updated stereotomy, while its design demonstrates current strategies that may be employed in the resolution of complex geometrical problems and bespoke fabrication of construction components for stereotomy. The proposed location for the vaulted structure is a garden with a lawn, where its visitors may find a pleasant shelter. This structure is placed in the lawn

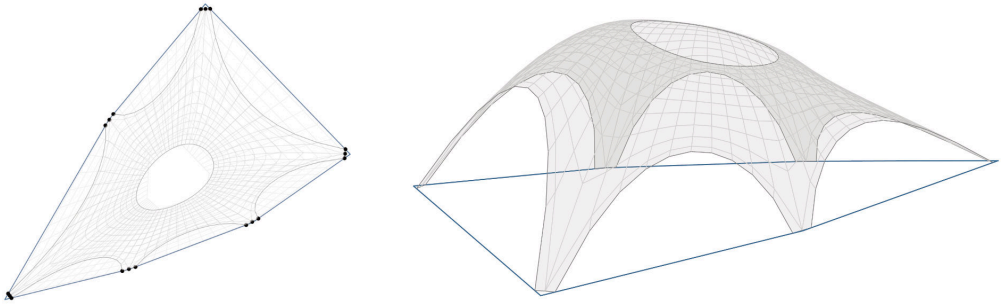


Figure 2
Ground plan of the Tamandua vault, showing the scalene triangle with supports marked. These were offset slightly, rendering an irregular hexagon; b) Perspective view of hanging model of the Tamandua Vault.

as a pavilion-like those found in English gardens. Stereotomic building fosters a construction made of non-perishable materials, with low demands for maintenance, adequate characteristics for an open-air construction.

### *Design and Macro Shape*

The proposed vault base shape is a scalene triangle, whose three sides present a different number of footings each. In the first side, there is only one wide opening with no central supports which may be understood as the main entrance; the second side features one central support resulting in two low arches, and the third side evokes an analogy with a portico for its sequence of four total supports. The interior of the vaulted roof is crowned with an oculus that naturally frames the skydome. The dimensions of the pavilion are subject to human scale, and they are adjusted during the form-finding process with proportion as a goal. As described above, the generating shape of this structure is a triangle which, together with the location of the supports, is the only manually controlled shape in this project, as the whole remainder resorts to algorithmic calculation. The whole algorithm is presented in Figure 1, where the various design and materialisation stages are highlighted. The first design step is to resolve the macro-shape of the structure which, in order to more dramatically express the language of a compressive bound stereotomic dry construction, closely follows an ideal thrust surface for a constant thickness shell; for this, it is devised a hanging model based in particle physics using the Kangaroo library created by Piker (2013). The hanging model takes shape of a zero thickness elastic surface subject to gravity forces and the aforementioned supports - while pre-computer architects were forced to use elaborate string models with weights attached and observe the final result in a mirror or in an inverted photograph, current simulation tools allows using a force opposite to that of gravity, generating the inverted model from the start. Despite the continuous nature of the surface, mathematical simulations are based in the finite element method (FEM), hence the need for a discretised topological network. A polygonal mesh is built using a given width for the supports, where all inner and outer vertices are purposed with weight and every connecting edge simulates elastic strings attached to these vertices in the near neighborhood, thus ensuring topological preservation. The computational model for the hanging surface is run and the result is evaluated, as illustrated in Figure 2. Two constraints are evaluated: vertical free space below the entrance arches, and the general proportion of the building. By adjusting the position of the initial support points and the magnitude of the vertical force, a form similar to the initial sketch is achieved. In the faceted classification (Azambuja Varela 2019) proposed in a previous article, this macro-shape is a Hanging Model whose label is "EAABA" (Equilibrium: Macro-Shape: Generation method: Bottom-up: Hanging model). Regarding its

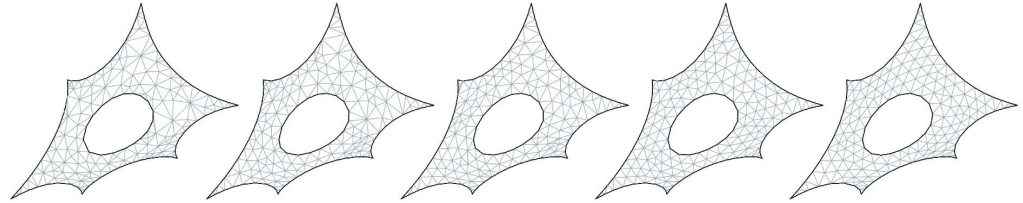



Figure 3
Five evolutive iterations of the process where the subdivision of thrust surface in a triangular mesh whose edges tend to a common length, while having these lengths reduced in parts where the curvature is higher.

continuity, it is a "EABB" (Equilibrium: Macro-Shape: Continuity: Continuous). Still, in the field of Equilibrium, its Structural Functioning is a "EBA" (Equilibrium: Structural Functioning: Compression only).

### *Surface subdivision strategy*

The subdivision of the thrust surface in discrete cells - reminding the meaning of the word discrete as "consisting of distinct or separate parts; not attached to others; unrelated; made up of distinct parts; discontinuous" - is tightly related to the generation of the voussoirs which, in turn, constrain and are constrained by the materialisation process. In order to maximize the usage of the baseboards which are part of the flexible mould which shall be the basis for all voussoirs fabrication, a subdivision that promotes a similar cell perimeter regarding its size and topology is chosen. As such, regular patterns are evaluated as an initial approach. Acute angles in the edges of a stone voussoir leave the tip of material unsupported and dependent in the capacity of material to avoid disaggregation. In the same line of thought, obtuse angles promote a much stronger cohesion between the different parts of the material. Taking this classic stonecutting rule of thumb into account, the tendentially hexagonal tessellation is thus selected as the most suitable. A possible approach to tackle the subdivision of a target complex surface involves its flattening, solving the problem two-dimensionally, and remap the solution to the original target surface (Hormann and Greiner 2000). This strategy creates an uniform tiling - topologically and general dimension wise - in the target surface. However, the cells follow the surface and are curved, a configuration not compatible to the mould system, which presupposes flat intrados. As such, the planarization of these cells detaches them from the thrust surface and some vertices become unaligned, a normal characteristic of convex tessellations of flat cells in anticlastic surfaces. In order to reduce this phenomenon, a valid strategy is to reduce the size of the cells in the highly curved surface areas (Figure 3), so that the difference between the points of the planar cell and its correspondent point in the thrust surface is reduced.

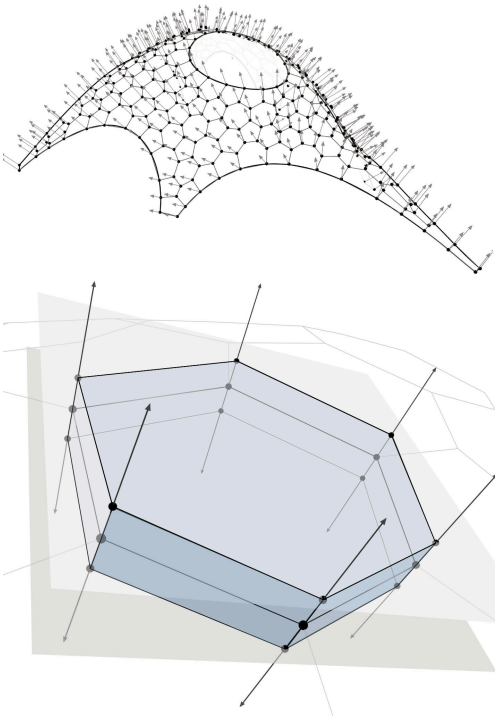
### *Voussoir geometric definition*

This part of the design process is where the shape evolves from its mathematically zero thickness (subdivision cell) abstraction into a volume (voussoir) becoming inextricably associated with stereotomy. The volume of a stereotomic structure comes from the thickness of its voussoirs, which is roughly the distance between intrados and extrados. In an arch, the resultant of compressive forces lies within a line called the line of thrust. Stable structures contain this line within its mass. Similarly, in a three-dimensional system, one can find a thrust surface where forces optimally flow, being wishfully in the innermost position within the section of the vaulted structure. The volume is created towards both sides, intrados and extrados, to maximize the incorporation of the thrust surface inside the structure's mass.

This stereotomic construction does not feature any kind of interlock and ideally no mortar, relying only in the direction of the contact surfaces (and eventually in some friction between voussoirs) to

Figure 4
Generating volume: a) Visualisation showing normal vectors to the thrust surface in the vertices of the voussoir cells; b) Generation of a voussoir: the vectors represent lines with the normal direction, which depart from the cell vertices (big dots).

avoid slippage; for this, the contact face should be as normal as possible to the thrust vector. Since every contact face connects each pair of intrados and extrados perimeters - because this project features "VBBBA" (Voussoirs: Intrados and Extrados: Perimeter: Correspondence: Analogous) - it is possible to use these perimeters to model the contact face. By placing a vector normal to the thrust surface in each of the endpoints if a cell edge - see Figure 4 - it is ensured that a ruled surface containing both those skew vectors is normal to the thrust surface in at least those initial points, and tendentially very approximate in the remaining part. These vectors are collinear to the voussoirs contact edges, and the extrados and intrados are parallel to the planar cells, each in half a distance of the full thickness of the voussoir. The intersection of an intrados plane with these vectors produces the vertices of the intrados and its correspondent perimeter in the form of a polygonal curve; the same applies for the extrados. The voussoir geometry is obtained by creating the missing contact ruled surface, either by connecting each pair of intrados and extrados edges, or each pair of consecutive contact edges. For the application of the variable mould described in a previous article (Azambuja Varela 2018), the voussoirs contact faces must be planar to be compatible with the flat aluminium bars which will compose the lateral side of the mould. Following the faceted classification, it is a "VCAB" (Voussoirs: Contact Surface: Geometry: Planar). As seen above, the perpendicularity of the contact edges to the thrust surface usually generates skew lines, hence the ruled surface connecting them. Because of the materialisation planar characteristic, a procedure for the planarisation of these faces must take place (Figure 5), as discussed in other works (Rippmann et al. 2016). A particle physics procedure is once again used to achieve an equilibrium under the conditions needed. In this case, each group of vertices contained in each contact face of the voussoir is assigned a CoPlanar goal, while collinear contact edges are tendentially kept in the original place. This algorithm will deform the contact faces to flat faces, thus altering the proposition of strictly normal geometry to the thrust surface. However, this difference is negligible and, usually, the pair of contact edges self compensate each other creating a planar surface whose normal is the average of the previous no planar iteration.



### *3D printed model*

Before any construction endeavors are taken, a functional model is constructed. This model is composed of 177 individually voussoirs at a 1:20 scale, seen in Figure 6. Their production is done in a Makerbot Replicator 2X Experimental 3D printer, which takes sensibly 15 hours in batches of 12 ABS plastic voussoirs, each 60 minutes. The small scale of the blocks is intended for a complete assembly with all participating members of the structural flow of forces at

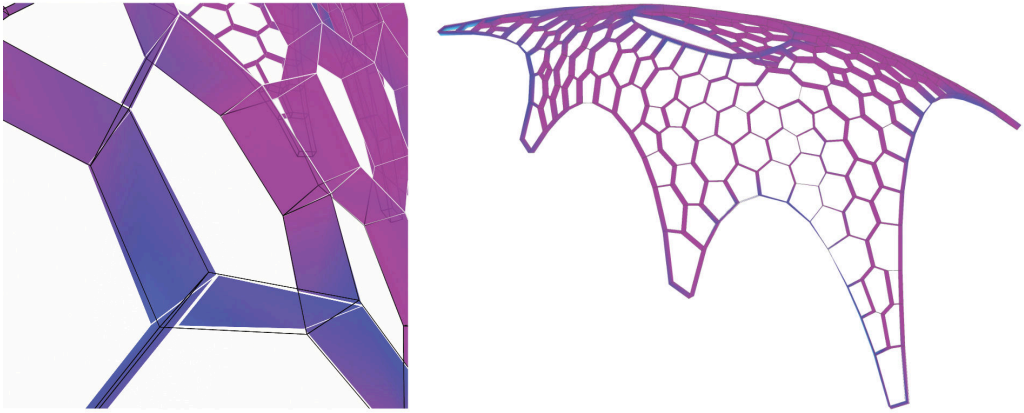


Figure 5
The black outline represents the planarization final result, while the coloured geometry represents the skew contact faces, in which purple is closest to its final position, and blue is farthest.

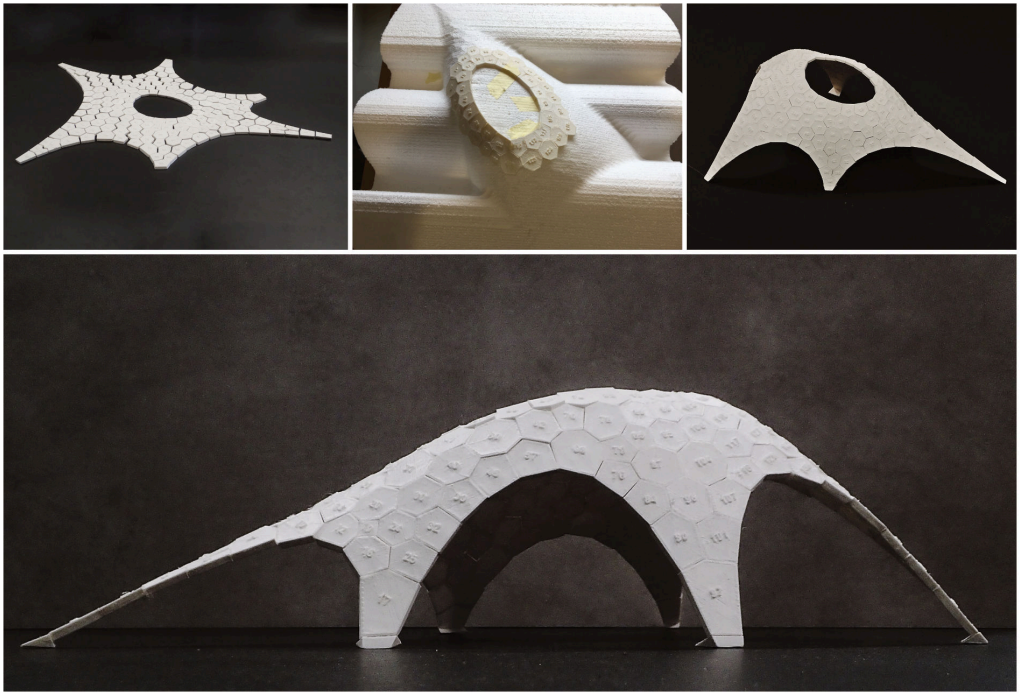


Figure 6
a) All the 177 individually voussoirs at a 1:20 scale laid out in a table; b) Model undergoing assembly; c, d) Assembled model.

play. This is possible because compression-only discrete structures are scalable, allowing for a reliable prediction of the stability of corresponding models and buildings (Heyman 1997). This complex shape is dependent of a centering in order to inform the exact angle and position of each voussoir in adjacency to the next. This centering was milled out of a single block of EPS, leaving imprinted the exact contours of the intrados. The small scale of the voussoirs, the printer's low resolution and the lightness of each piece denies the possibility of a complete mortarless assembly of the model, which is put together with small points of hot melt adhesive. The complexity of the designed shape calls for a more insightful analysis than a regular vault (such as a barrel vault, or fan vault), and the access to rapid prototyping allows for the creation of a model which is able to give this output. This duality between the needed analysis and the possibility of rapid prototyping is part of a symbiotic relationship often found in the osmosis between new technology and novel expressions in architecture. If on one hand rapid prototyping allows for the accessible creation of a model of such a complex shape, on the other hand, this design is also only possible because we have the tools to evaluate it. Besides evaluating structural aspects of the construction, the model is also instrumental in analysing the design, easily observable from various perspectives.

### *Voussoir prototype*

The fabrication of the voussoirs (Figure 7) follows all the same principles used in the reinforced, reusable, reconfigurable molds for cast voussoirs presented in the article of the same name (Azambuja Varela 2019). Recapitulating the main principles, the fabrication used the variable mould system with the large aluminium planar bars as contact face mould parts, and narrow rectangular iron bars as supports. These supports are held in their accurate position and angle by insertion into angled holes milled by a 6 axis robot or 5 axis CNC. This mould's components are reusable, promoting the production of voussoirs without waste and avoiding the need for 3D printing systems precise enough (<1mm) and capable of handling construction final material. For the insertion of the support bars, specially angled holes mimicking the angles of the voussoir contact edges are milled with a robot. Regarding the proper casting of the voussoir, the procedures in the work site mimic those of a previously built tri-arch.

There, special mixes were tried until an optimal mix of cement water and foam is chosen. The process started with the making of a simple cement paste (2,5 kg of cement and 1,0 l of water), to which foam (produced by mixing a foaming agent (AG-1) with high-pressure air through a specialized nozzle) was added (2,0 l). The foam was mixed with the cement, making it a very light mixture that was poured into the mould, previously coated with vaseline, a demoulding agent, to ensure that the less dense concrete mixture would not adhere to the mould surface. The voussoirs were produced one by one, and after each demoulding, the voussoir was carefully removed and left to cure in order to achieve its full strength. A run of trials and errors allows to reach the conclusion that 48 hours is the minimum time for a successful foam concrete demoulding to take place. Due to the large size of this prototype voussoir, it was left to cure for 36 hours before demoulding. The synthesis of the process is documented in figure 7, where the various stages can be evaluated.

## CONCLUSION

This article discussed the design and materialisation processes of the Tamandua Vault (Figure 8), a self-proposed demonstrative project whose main feature is the reusability of the molds used to fabricate its building blocks. It documented the various processes essential to control a stereotomic design in a shape with a strong level of complexity. The processes discussed include computer simulation of hanging models, strategies for creating an informed subdivision of a surface, and the geometric control of the angles in the formulation of voussoirs as structurally performative volumes. It was also presented

Figure 7
Various stages of the Tamandua Vault voussoir prototype fabrication: a) Milled baseboard; b,c) Mould filled with concrete; d) Contact face bars removed, exposing contact faces; e) Contact edge bars removed, exposing full block; f) Finalised block.

Figure 8
a) Simulation of the Tamandua Vault as built; b) Inner view with the contact faces in first plane and oculus in the second plane.

a complete 3D printed structural scaled model of the vault, as well as the fabrication of a representative voussoir at full scale and in the final material, foam concrete. The developed processes for the Tamandua Vault were guided by a holistic approach in various design stages and the materialisation processes which illustrate current possibilities for an augmented stereotomy.

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# When the Geometry Informs the Algorithm

## *A hybrid visual/textual programming framework for facade design*

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*Facade design is becoming increasingly complex, forcing architects to more frequently resort to analysis and optimization processes. However, these processes are time-consuming and require the coordination of multiple tools. Algorithmic Design (AD) has the potential to overcome these limitations through the use of algorithms implemented in Textual Programming Languages (TPLs) or Visual Programming Languages (VPLs). VPLs are more used in architecture due to their smoother learning curve and user-friendliness, but TPLs are better suited than VPLs for handling complex AD problems. To make TPLs more appealing to architects, we incorporated VPLs' features in the textual paradigm, namely, Visual Input Mechanisms (VIMs). In this paper, we propose an extension to an existing AD framework for the design exploration, analysis, and optimization of facades to support a TPL-based approach that handles VIMs.*

**Keywords:** *Algorithmic Design, Facade Design, Textual Languages, Visual Input*

## INTRODUCTION

Architectural design needs to consider the currently growing design constraints, e.g., environmental (Picco et al. 2014), structural (El Sheikh 2011), and aesthetical (Schulz 1971; Schittich 2006), often forcing architects to resort to analysis and optimization processes (Machairas et al. 2014), although with two serious limitations: (1) these processes are typically time-consuming and, as the available time is usually short, the final solutions are often only partially improved (Nguyen et al. 2014); and (2) analysis processes involve multiple tools with different data formats, causing information losses and the accumulation of design errors resulting from imperfect data transfers between tools (Leitão et al. 2017). These shortcomings hinder the adoption of analysis/optimization processes, confining their application to latter design stages (Turrin et al. 2011; Shi 2010) where, unfortunately, their impact in the solution's performance is limited (Konis et al. 2016). Algorithmic Design (AD) promises to overcome these limitations by facilitating the analysis and optimization of architectural designs (Alfaris and Merello 2008) from early stages. AD uses algorithms to create designs, allowing for more complex design solutions, facilitating changes, and automating repetitive tasks, in particular, the *generation-analysis-regeneration* cycle, typical of optimization processes.

AD can be implemented using Textual Programming Languages (TPLs) or Visual Programming Languages (VPLs). Architects tend to prefer VPLs not only due to their visual nature, but also because TPLs are

less intuitive, as well as more difficult to learn and use than VPLs. Additionally, TPLs rarely support the Visual Input Mechanisms (VIMs) of most VPLs that allow for the direct use of graphical entities, such as points, curves, and surfaces, as inputs to the AD program. However, TPLs show greater potential for large-scale designs (Leitão et al. 2012; Celani and Vaz 2012; Wortmann and Tunçer 2017) and, once mastered, they tend to be more productive. Given TPLs' and VPLs' different advantages, it is appropriate to consider their combination, either by incorporating textual programming components in VPLs, as demonstrated by *Grasshopper*'s *Python* component, or by extending TPLs with VIMs (Sammer et al. 2019). The latter will be the focus of this paper.

We propose extending a TPL-based AD framework, whose domain of application is building facades, to support VIMs. The extended framework provides several predefined algorithms for the design, analysis, and optimization of facades, now coupled with the most relevant VIMs for specifying the constraints that affect facade design.

In the past, this framework addressed architectural problems integrating environmental factors (Caetano et al. 2018) and design rationalization (Caetano and Leitão 2018). In this paper, we focus on its combination with VIMs. The research entailed three stages: (1) studying the differences between a Visual Input (VI) and a Textual Input (TI); (2) understanding how a VI can be incorporated within a text-based AD approach; (3) implementing a set of VIMs in the algorithmic framework for facade design.

## BACKGROUND

AD requires programming experience, which most architects do not have. Fortunately, several Programming Languages (PLs) were developed to facilitate the learning process: some are textual, such as *Processing*, *Racket*, and *Python*, but the most popular ones among architects are visual, such as *Generative Components*, *Dynamo*, and *Grasshopper*. They allow users to create AD programs by manipulating graphical elements (Janssen 2014), thus being more intuitive and productive for beginners when compared with TPLs (Zboinska 2015). VPLs also integrate features that facilitate the programming task, namely traceability, real-time feedback (Leitão et al. 2014), and VIMs.

Despite their appeal, VPLs still present several limitations: (1) they lack scalability, making large programs difficult to understand and modify (Leitão and Santos 2011; Janssen 2014); (2) they confine users to the predefined modules/components available in each VPL, hindering solutions that need more advanced features (Zboinska 2015); and (3) they lose their real-time feedback capabilities when dealing with more computationally-intensive designs (Leitão et al. 2014). As a result, for complex design problems, architects tend to use TPLs (Leitão et al. 2012), proving the inability of VPLs for long-term use (Noone and Mooney 2018).

Unfortunately, it is difficult to transition from a VPL to a TPL, and more so when one is accustomed to VIMs, since these mechanisms are rarely available in TPLs. A possible strategy to facilitate this transition and flatten TPLs' learning curve is to incorporate some VPLs features in TPLs to make them more intuitive and, thus, more adequate for teaching purposes; a perspective already addressed in the past (Sammer et al. 2019). In this paper, we go further by extending a TPL-based AD framework for facade design to also support VIMs, while preserving its capability to generate, analyze, and optimize large-scale designs. In the following sections we explain the framework and the proposed extension, and we evaluate it with a case study.

## ALGORITHMIC FRAMEWORK FOR FACADE DESIGN

Any AD framework must address the typical variability of architectural design in a way that a computer understands. Computers operate upon a set of instructions transmitted via PLs and, while the first PLs were difficult to learn and use, the current ones are getting closer to the universal language of mathematics. Therefore, the implementation of the AD

framework for facade design considered the formalism of mathematics, being organized in a fivefold classification: (1) *Geometry*, to define the overall geometry of the building facade; (2) *Pattern*, to explore several geometric facade patterns through the combination of different shapes and geometric transformations; (3) *Distribution*, to create different facade grids and pattern distributions; (4) *Optimization*, to improve the design according to fitness goals; and (5) *Rationalization*, to make a balance between the conceptual design intent and the solution's feasibility. Each category contains a set of predefined algorithms that are portable between different modelling tools, namely *AutoCAD*, *Rhinoceros*, and *Revit*, and analysis tools, namely *Robot* and *Radiance*, among others. Despite originally supporting only TIs, in this paper, we extend the AD framework to also deal with VIs.

In general, a VI represents a manually created geometry in a design tool, whereas a TI comprises a textual description. While the latter can be directly combined with any algorithm available in the framework, the former needs to be first converted into a format suiting the algorithm. To this end, we extended the AD framework with some VIMs that allow the use of shapes created in the modelling tools as input to the framework's algorithms. These functionalities apply principles explored in previous research (Sammer et al. 2019), thus evaluating their suitability for architectural design and, more specifically, facade design.

The available VIMs rely on the selection of one or more shapes in the modeling tool, which are then provided as VI to the algorithms. During this process, users can decide whether they want to preserve a dependency between the AD program and the selected shapes. In the affirmative case, the AD program is automatically rerun every time the input shapes are changed in the modeling tool; otherwise, it only considers these changes when the shapes are re-selected. For the latter scenario, the framework resorts to *metaprogramming* techniques, i.e., the use of programs to generate other programs (Czarnecki et al. 2002) that, in this case, correspond to equivalent algorithmic descriptions of the existing VIs in the modeling tool. To make the AD program independent from a given VI, we replace the program fragment representing the VIM with the generated program fragment reproducing that same VI. This allows the latter to be stored in the AD program, no longer reacting to changes made to its original shape, and to be reproduced either in the same or in another modeling tool. This enables the framework to have a general application, not restricting the available functionalities to a specific tool, while permitting to take advantage of VIs produced in multiple modelling environments. Nevertheless, the resulting algorithmic descriptions are non-parametric, which means they represent and reproduce only the original VI and not variations of it. Further details on the available functionalities and their implementation can be found in Sammer et al. (2019).

## EVALUATION

In this section, we evaluate the framework in a case study, following a three-phase process: first, we model the original case study using a purely AD approach; then, we explore different design variations of it by applying only TIs; and, lastly, we generate the same design variations but using only VIs. In this evaluation, we use *Khepri* (Leitão et al. 2019), a descendent of the AD tool *Rosetta* (Lopes and Leitão 2011).

### *Case Study*

Our case study is inspired by the facade of the *Formstelle* building designed by *Format Elf Architekte*, which is composed by several hexagonal apertures of different sizes, creating a gradual stain in the facade's central area (figure 1, top). We selected this case study due to its large design space, that can be easily explored using VIs. To reproduce this design using the algorithmic framework, we select algorithms from: (1) the *Geometry* category, to produce the surface's spatial locations on which we want to distribute the hexagonal openings (figure 1A); (2) the *Distribution* category, to arrange the apertures in a rhombus mesh (figure 1B); and (3) the *Pattern* category, to

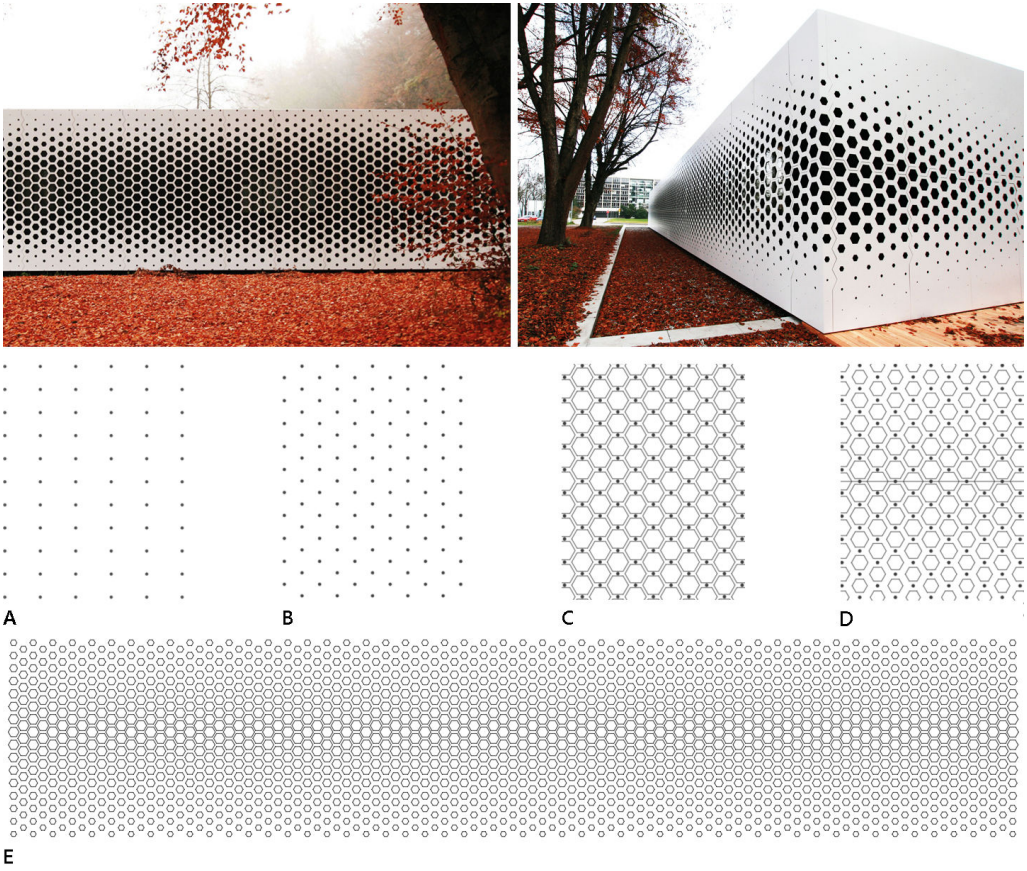


Figure 1
Top: Formstelle building in Töging am Inn, Germany (courtesy of Format Elf Architekten); Bottom: the case study's algorithmic development: A. surface original points; B. rhombus mesh creation; C. hexagonal elements' placement; D. hexagonal elements' size variation; E. final facade design.

create a hexagonal aperture in each location (figure 1C) and to control their size according to a rule that, in this case, corresponds to the elements' distance to the facade's horizontal axis (figure 1D). Then, we combine these algorithms through function composition techniques: we use the first algorithm (straight) as input for the second one ($grid_{rhombus}$), which returns a set of locations distributed in a rhombus-shaped grid; then, these locations are used as input for the other two algorithms (regularPolygon and scale), which create the hexagonal elements, in the first case, and control their size according to their distance to the facade's horizontal axis, in the second case.

### *Geometric Exploration*

This section focuses on the application of design changes to our case study following two strategies: one using only TIs and the other using VIs.

**Textual Inputs.** At this stage, we explore several variations of our case study using only TIs. To obtain the original design (figure 1E), we combine the scale

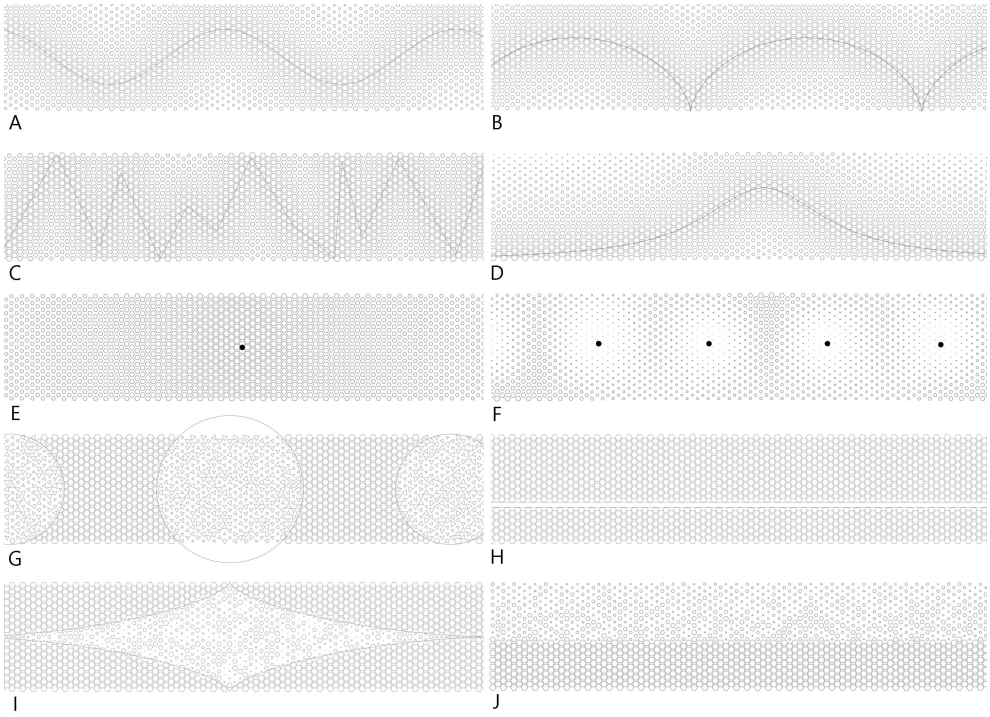


Figure 2
Case study design variations using TIs: defining curves (A-D) or points (E-F) to change the size of the apertures, or areas to apply certain design variations (G-J).

algorithm with another one acting as an *attractor* ($attractor_{curve}$), which receives as input a curve and an attraction intensity factor (from 0 to 1) and returns, for each facade element, a value that differs according to its distance to the curve. We provide this algorithm with another one describing a horizontal straight curve.

To change the original design, we can use other curves (figures 2A to 2D) or use the $attractor_{points}$ algorithm and set one (figure 2E) or more points (figure 2F) as attractors. We can also select the facade areas where we want to apply design variations, like creating elements of different shapes (figure 2G) or sizes (figures 2I and 2J) or simply having no elements (figure 2H). For this we have the $affected_{areas}$ algorithm, which receives closed curves delimiting the area(s) to change and the transformation rules to apply and their intensity factors. In practice, this algorithm tests if each element matches the given areas and, in case it does, it applies the transformation(s) to it, otherwise, it keeps the element unchanged.

**Visual Inputs.** To change our case study using VIs, we have to manually produce in the design tool different shapes according to the requirements of the selected algorithms, e.g., points (figure 3E) and curves (figures 3A to 3D) in case we use the $attractor_{points}$ and $attractor_{curve}$ algorithms, or closed curves delimiting areas in case we apply the $affected_{areas}$ algorithm (figures 3F to 3J). Note that, here, the $attractor_{points}$, $attractor_{curve}$, and $affected_{areas}$ algorithms receive as input one or more geometric entities manually produced in the modelling tool. To allow this, the framework resorts to *metaprogramming* techniques to convert non-algorithmic elements into

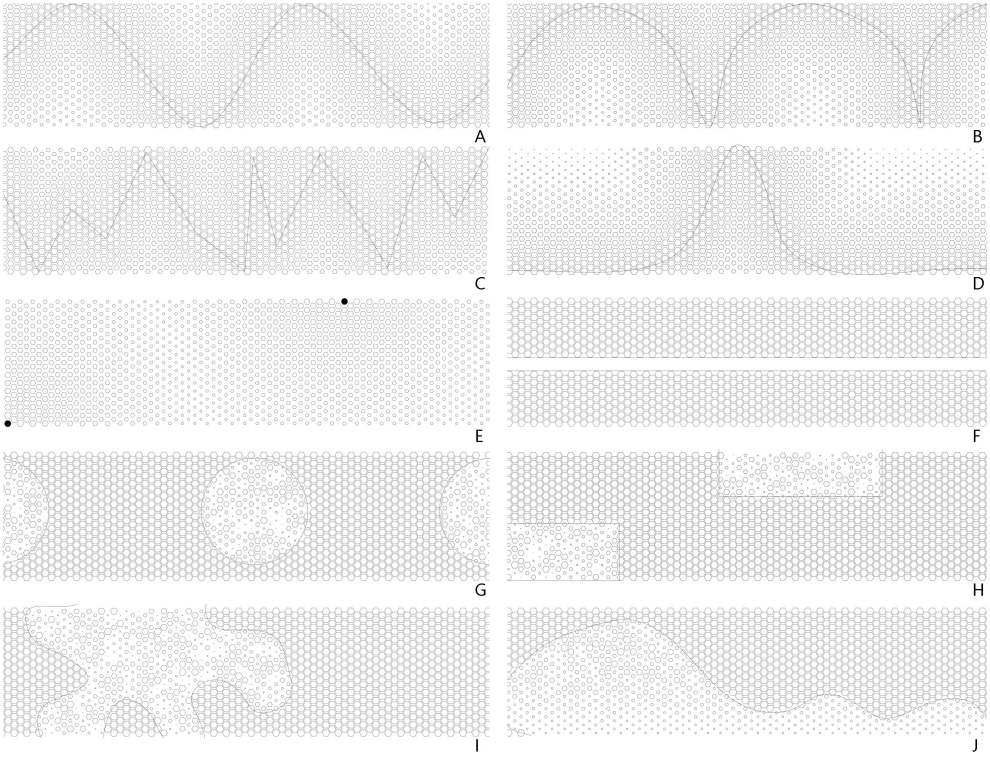


Figure 3
Case study design variations using VIs: creating curves (A-D), points (E) in the modeling tool to change the apertures' size, or areas to apply different design variations (F-J).

algorithmic ones. The resulting scenario enables us to constantly interact with the design tool and iteratively combine the VIs with the framework algorithms, including analysis and optimization ones. Also, it allows us to change the VIs' resulting algorithmic descriptions to achieve aesthetic or performance goals, as well as to store them in the framework, making them available for future projects.

As an example, to optimize our case study in terms of natural lighting and privacy levels, we need to iteratively analyze several design variations to find the solution that best suits both goals. In a typical design process using VIs, i.e., where the selected input is a shape manually created in the design tool, the analysis of different design configurations requires us to manually change the input shape before starting a new analysis cycle; a scenario that clearly hinders the automation of multiple analyses in an optimization process. Our framework overcomes this limitation, as the available algorithms handle all inputs in the same way, independently of being textual or visual inputs. In practice, while the former directly informs the optimization process, the latter is first converted into an algorithm to then inform the optimization. This means that we can use both VIs and TIs to drive optimization processes. Figure 4 shows an example where the optimization algorithm automatically changes both the position of a VI, i.e., a straight curve, and its intensity factor, producing a pool of results from which the architect can choose the one that most pleases him.

## DISCUSSION

This section analyzes the previous approaches, making some final considerations on the benefits of integrating VIMs in a textual-based AD framework.

### *Portability*

Concerning the portability of each approach, we conclude TIs are more advantageous because they (1) are independent from the modeling tool, (2) generate the exact same results in different tools, (3) store all the information needed to reproduce the results of their application at any time, and (4) can be easily converted into their corresponding visual representation. Contrarily, as a VI is typically created in a specific modelling tool, the AD programs using it become dependent on both the tool and the file containing the VI. Our framework overcomes these limitations by converting VIs into TIs, allowing the former to benefit from some of the latter's advantages in terms of portability. Also, when a VI is stable, i.e., when we no longer want to modify it, we can store its algorithmic description, becoming henceforth just part of a larger algorithm. As an example, consider figure 3I: in a first stage, we modelled different curves in the design tool, while applying the same transformation rule to the elements, i.e., a random size variation. When satisfied, we stored the final curve and, thereafter, we explored various transformations to the hexagonal elements without ever having to reselect the curve in the design tool (figure 5).

### *Ability to Generate Geometries*

Regarding the ease that each approach has in generating different types of geometric information, we conclude that both have advantages over the other depending on the context. In a situation where model-user interaction is critical, i.e., where the architect has little or no AD experience, the use of VIs is essential, as it allows the user to freely create/manipulate the VI in the modeling tool and immediately see the resulting solution. VIs are also advantageous when we need to use pre-existing geometries or create organic/free-form shapes, whose corresponding mathematical descriptions are often difficult to derive. Contrarily, TIs are advantageous when we need to use known mathematical curves or surfaces as input or to provide the output of an AD program as input to another.

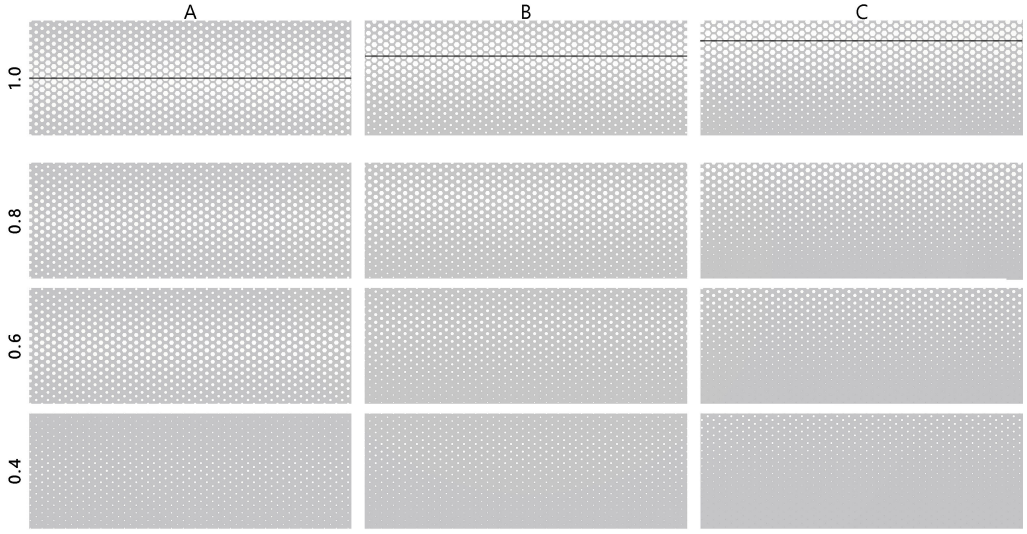


Figure 4
Case study optimization: analysis of solutions resulting from different intensity factors (0.4 to 1.0) and attractor-curve positions; (A) original position; (B-C) two of the positions tested.

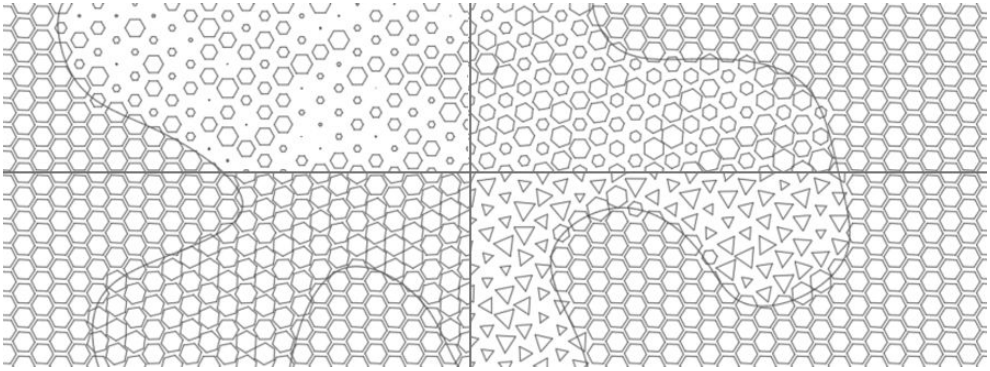

Figure 5
Different design variations using the same free-form curve of figure 3I.

These relative advantages are visible in the previous examples: while, in figure 2A, the mathematical sine curve resulting from a TI evidences a more perfect sinusoidal effect than the one manually created in figure 3A, the implementation of TIs representing the free-form curves in figures 3I and 3J would require us to algorithmically describe each point of the curve, which would be more laborious and time-consuming than modeling them directly in the modelling tool.

### *Flexibility*

Based on the above considerations we conclude that TIs are usually more accurate and portable than VIs. Nevertheless, as our framework handles VIs and TIs similarly, both end up having almost the same flexibility. Still, while most TIs correspond to parametric algorithmic descriptions, the conversion of VIs into TIs results in non-parametric ones. To obtain parametric descriptions, we need to spend extra time and effort with their implementation, which also requires programming experience. Moreover, finding the parametric descriptions of VIs can be a difficult task, as it happens with the curves in figures 3C, 3I, and 3J.

As an example, consider again the designs in figure 2A and 3A. In the first case, the sine curve is described by a parametric function, allowing us to easily alter its parameters, namely amplitude, phase, and frequency, and obtain different curves as result. This does not happen with the second example, because it uses a manually produced curve and, although the framework can convert the curve into an algorithm, the latter is not parametric. Thus, to alter its amplitude, frequency, or phase, we need to either implement its parametric description or manually create a new curve in the modelling tool with the desired modifications.

The differences between VIs and TIs become relevant in analysis and optimization processes, where VIs evidence more limitations due to their lack of portability, limited flexibility, and CAD-dependency. TIs, due to their greater flexibility, end up giving more freedom and autonomy to the optimization process, widening the range of design variations explored and, therefore, increasing the likelihood of finding better-performing solutions.

As a final example, consider the designs in figures 2D and 3D. The first one uses the parametric description of the *witch of Agnesi* curve as TI, allowing us to easily obtain different curve instances by changing its parameters. The second one uses an approximation of the same curve modelled in the design tool as VI, which is then converted by the framework into its algorithmic but non-parametric description. In practice, when combining the TI with the optimization algorithm, we can make the latter control the former's parameters throughout the entire process, obtaining better-performing solutions. When combining the VI with the optimization algorithm, the latter

can also modify the former by changing its algorithmic description, however, it can only change the spatial locations that define the curve individually because there is no parametric dependency between them.

## CONCLUSION

The architectural practice is moving towards an increasing use of analysis and optimization processes. However, these processes are time-consuming and the various types of analysis require data transfers between multiple tools, causing information losses and the accumulation of design errors (Leitão et al. 2017). These shortcomings hinder the adoption of analysis and optimization processes in architecture.

We can overcome these limitations by combining analysis and optimization with Algorithmic Design (AD) (Alfaris and Merello 2008), which is a design approach based on the use of algorithms that demonstrates great potential for automating the *generation-analysis-regeneration* cycle typical of optimization processes. AD can resort to Textual Programming Languages (TPLs) or Visual Programming Languages (VPLs), the latter being the most preferred ones by architects due to their visual nature and ability to support Visual Input Mechanisms (VIMs), making them more intuitive and easier to learn and use. However, TPLs are more expressive, supporting the development of large-scale designs (Leitão et al. 2012; Celani and Vaz 2012; Wortmann and Tunçer 2017). Given their different advantages, it is beneficial to combine them in a hybrid approach.

AD is not new and was already applied to carry out complex projects that otherwise would be unfeasible. It has also proved its ability to reduce construction costs and waste, while improving the quality of the design solutions. We expect that, in the near future, AD will be integrated in all stages of the design process, and in most design studios and construction companies.

In this paper, we extended a TPL-based AD framework for facade design, analysis, and optimization to support VIMs. We explained the features that were integrated in the framework to handle different types of Visual Inputs (VIs), making them portable across different design tools, as well as suitable to be integrated in a text-based AD approach. We used some of them to describe different graphical inputs, such as points, curves, and areas, that constrained the facade design. We evaluated the framework in the development of a case study, for which we used both VIs and Textual Inputs (TIs), concluding that both have advantages depending on the design situation. Still, TIs evidenced significant advantages regarding accuracy, portability, and flexibility. Moreover, when combined with the framework's optimization algorithms, VIs proved to be more limited due to lack of flexibility and parametricity.

As future work, we plan to extend the framework with more VIMs, such as images, 3D scans, and point clouds, and improve the already existing ones, especially to allow the direct conversion of a VI into its parametric representation. Also, we plan to research the use of VIMs for other AD problems, particularly, those addressing 3D spatial configurations, such as paths for cameras in rendering tasks, locations to operate as generators of 3D volumetric forms or as distributors of building elements in space, or surfaces for terrain modeling tasks or for creating architectural elements such as roof space frames and shading structures.

## ACKNOWLEDGEMENTS

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# Performance Oriented Design Framework for Early Tall Building form Development

## *Seismic architecture view*

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*Today, the wide variety of social requirements for commercial or aesthetic purposes and the power of Computer Aided Architectural Design (CAAD) tools result in designing tall buildings with complex forms. On the other hand, tall building architectural form has significant effects on its seismic performance. Seismic design provisions and guidelines divide forms to regular and irregular, recommend avoiding irregular ones, and proposed some seismic-efficient design strategies. However, they do not provide any evaluation factor for quantifying the range and effectiveness of the proposed design strategies. Furthermore, they do not propose any framework for the optimum architectural design of complex form with No-irregularities either. Addressing this lack of fit, this research proposes a design framework based on POD method to perform an initial seismic performance evaluation for regular complex forms in the conceptual stage of architectural design. The proposed framework used to optimize a taper-twisted tall building form regarding its seismic performance. The results show a significant correlation between the architectural decisions and building seismic performance, even in the forms considered as regular based on the definitions which should be considered in the very first steps of form developments*

**Keywords:** *Performance-Based Design, Tall Building, Form Development, Seismic Architecture*

## INTRODUCTION

Designing tall buildings are influenced by several criteria that may have different levels of impact on its architectural form. Generally, building architectural form defines 3D-shape, size, and relations of building dimensions and the location of structural members in plan and vertical layout. Most of the seismic design provisions, divide buildings to regular and irregular categories based on their plan and form. Based on their definition, a building is considered regular if it has a uniform distribution of mass, stiffness, strength, and structural members throughout the elevation and plan of the building. An irregular building has a non-uniform distribution in one or a combination of the aforementioned properties in any direction (vertical and/or horizontal). In the seismic design provisions, guidelines recommended avoiding irregularity to ensure a better overall seismic performance of a building during an earthquake(FEMA-445) (PEERc, 2010). However, if one maintains the regularity of the form, according to the definitions in the provisions mentioned earlier, there are no criteria for prioritizing a form to another regarding the seismic performance. According to the inherent close relation of functional, aesthetic, and structural issues in tall buildings, this issue is much more important in these types of buildings. Many tall buildings have a complex form according to the needs of the project, which may not include any of the irregularities mentioned in the provisions and thus considered as a regular form. Still, evaluating their seismic response and finding the tractable solution(s) for improving it, is challenging, especially by an architect. To this date, none of the seismic design provisions and guidelines propose any criteria for optimizing the seismic performance of so-called complex-regular forms. The Interrelation between the form and seismic performance of tall buildings has been the subject of numerous research works. These works can be divided into two general approaches; In the first approach, the researches address the issue from a qualitative point of view. Some of them point out that earthquake affects whole building and all entities involved in the construction process, including architects, should have their own roles and responsibilities for earthquake resistance(Noorifard & et.al, 2018) (Mahdavinejad & et.al, 2012) . Others focused on exploring the form variables in the realm of architectural decisions that affect building seismic performance (Dražić & et.al, 2016) (Arnold & Reitherman , 1981) (Arnold C. , 1996). They propose some features as the best attributes for buildings in the seismic regions such as continuous load path, low height-to base ratio, symmetrical plan shape, etc. (Charleson, 2008) (Hameed Hussein & et.al, 2017) (Arnold C. , 2006). While these features are essential, they do not provide any evaluation criteria or general methods to quantifying the acceptable limits for their implementation. The second approach mostly focuses on the adverse effect of the regular form complexity on the seismic performance from a quantitative point of view. However, the ratio of scientific studies on regular-complex forms within all the work done on seismic design is meager. In this approach, the researchers analyzed the effect of different tall building forms with different kinds of complexities on their seismic response (Kazemi & et al, 2018) (Khoraskani & et al, 2018). The correlation of the suggested complex indicators and the overall seismic performance of the structure is generally evaluated in terms of structural weight, deflection, or utilization (Kazemi & et.al, 2018). While all of the researches, as mentioned earlier, emphasized the significance of the form complexity effect on the seismic performance of tall buildings, they are mainly suggesting some tuning in the architectural form or some design strategies for the particular cases that they explored. Whereas, various modifications in the architectural form in terms of the plan and vertical layout may have different rates of impact on its seismic performance, though a linear trend is not reachable (due to the inherent properties of some geometries)(Ardekani & et al, 2019). In this work, we propose a seismic design framework and evaluation criteria to address this problem. The research goal is to provide the architects with qualitative insight and initial quantitative evaluation of the seismic .performance

of any regular-complex form during the conceptual design phase.

## SEISMIC ARCHITECTURE; THE DECISIVE ROLE OF ARCHITECTURAL DECISIONS

The term "an Earthquake Architecture", first used by Arnold (Arnold & Reitherman , 1982), generally refers to considering the effect of form on the building's seismic performance (Abolvardi, 2011, pp. 35-38). Particularly speaking, Seismic Architecture approach emphasizes that the architectural decisions about the form affect not only the size of the structural elements, also the lateral load distribution and thus the building's response to these load (Charleson, 2008, pp. 94-98) . Studies on the effects produced by numerous earthquakes have confirmed how much of the damage and subsequent building collapses can be attributed the building form (Arnold C. , 1996, pp. 1-3). This led to the introduction of 'form irregularities'. The 1988 Uniform Building Code first specified provisions to define irregularities by certain metrics such as comparing story stiffness based on geometric parameters to determine if a soft-story is present in the structure (FEMA-749, 2010). Architectural design rules thus gradually entered all seismic regulations around the world (Fajfar, 2018, pp. 5-7). For tall buildings, the form has a much more sizable effect on seismic performance. This is not only because they have a high aspect ratio, which makes the design more challenging due to excessive lateral load, but also the distribution of mass, structural elements (and thus its strength and stiffness), through the height is drastically affected by their forms. There are many factors in building form that have considerable effects on its seismic behavior; even in totally regular ones. Building form largely determines the ways in which seismic forces are distributed throughout the building and their relative magnitudes (Charleson, 2008, pp. 17-18) Thus, the discussion of form influence on seismic performance becomes the identification of form variables that affect the distribution of forces. They are decided by the architect in the conceptual design phase before the structural engineer makes his contribution and as a result, the initial conceptual design of a building is extremely important for the behavior of the building during an earthquake. For example, tilted tall buildings have excessive initial lateral deformations due to eccentric gravity loads (Moon K. S., 2015, p. 32). This can be rectified (or at least minimized), if the architect design the form such that the center of mass (CM) coincides with the center of rigidity (CR) to reduce the overturning moment and consequently reduce the tip deflection (Arup, 2007, pp. 443-445). Another example is the twisted tall buildings that possess smaller lateral stiffness compared to the straight buildings (Moon K. S., 2015, p. 31). One can compensate for this shortcoming by altering the key architectural decisions in the conceptual design phase, such as increasing the core area and adjusting the rate of twist throughout the height (that increases the torsional stiffness) (Arup, 2007, p. 447). These two examples prove that by understanding the seismic performance of a form, one can use form variables (architectural parameters that are usually set in the conceptual design phase) as an advantage to improve the overall behavior of the building. In many studies, the relationship between form and seismic performance has been qualitatively investigated and some strategies proposed in order to optimize the building form (mentioned as the first approach researches in the introduction). However, the effective variables for making those changes have been introduced in a scattered manner in each source with different categories. Since this research is going to propose a performance-oriented framework using parametric design, a brief classification of important form variables that contribute to the building's seismic performance is needed. Figure 1 shows a proposed seismic desirable building form according to (Arnold C. , 2006)(Figure 1) and Table 1 provides a brief classification of the effective variables that are derived from those forms(Table1).

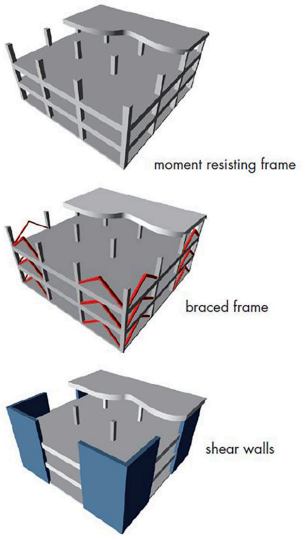



Figure 1
An optimum seismic-efficient building form .proposed by (Arnold C. , 2006).

| Seismic Design Goals | Desirable Seismic Feature | Corresponded Variable in The Form |
|---|---|---|
| Avoid stress concentration | Short Span | Vertical Structural members |
| | Continues load path | |
| | Identical vertical Resistance | |
| | Equal Floor Height | Floor Height |
| Minimize Overturning Tendency | Low Height/Base Ratio | Total Height |
| | No Cantilever | Plan Dimension |
| | Uniform Section and Elevation | 3d Transformation |
| | No Title | |
| Minimize Torsion Tendency | Seismic resitance Elements at Perimeter | Horizontal Structural Members |
| | Identical Resistance on both the axis | |
| | Symmetrical Plan Shape | Core Location in Plan |

Table 1
Form variables that affect building seismic performance(Authors).

## RESEARCH METHODOLOGY, PERFORMANCE ORIENTED DESIGN

The concept of Performance-Oriented Design (POD) has emerged, as a design method in which building performance becomes a guiding criterion for its architectural design (Kolarevic, 2003). In this design method, using numeric design assessments are related to the learning process and knowledge available or generated during the design process (Turin et al., 2011, p. 3). This research aims to use building seismic performances as criteria to optimize form generation in the conceptual design stage. In fact, the seismic performance would not act only as of the controlling criteria but also indirectly as the form generator; since it is the main reason that causes the change in form generating variables. Achieving this goal based on POD method will involve three phases: Strategy-Definition, Model-Making, and Solution-Assessment (Turin & et.al, 2013, p. 521). Each of which would be discussed in detail in the following.

### *Strategy-Definition*

In this phase, first, the desirable seismic performance and its relevant criteria and evaluation factors are defined. Then, a seismic design and analysis method is chosen, which is appropriate for an initial architectural design stage.

**a. Desirable Seismic Performance.** "Performance-Based Seismic Design" (PBSD) is a design approach based on deformation capacity and damage index which is common to be used particularly for the seismic design of tall buildings (CTBUH, 2017, p. 12). This approach requires a building to be designed to meet specific performance objectives under the action of the Frequent to Very Rarer seismic events that it may experience in its lifetime (Figure 2). Generally, the decision as to which building should be designed according to which earthquake probability/s and the relative expected performance depends on the important factor of the building and the risk factor of the design region (FEMA P-751, 2012, pp. 57-59). Tall buildings are considered as important/very important buildings due to their high occupancy in almost all of the building provisions. Therefore, they should remain "Fully Operational" through the "Frequent Earthquakes" (which is known as Service Level Earthquake Load)(SLEQ); regardless of which lateral load (wind or earthquake) governing the design (PEERc, 2010, p. 45). The corresponded evaluation index for fully operational performance is the "Inter-story Drift Ratio" (IDR), which can be derived by dividing the translational displacement difference between two consecutive floors divided by the story height(FEMA-749, 2010, p. 85). From a broader perspective, the

IDR is not only playing a vital role in structural and nonstructural components damage but is also a crucial indicator of the P-Δ effect (FEMA-749, 2010, p. 221). Design for drift and lateral stability is an issue that should be addressed in the early stages of design development, especially in tall buildings in which the drift criteria can become a governing factor in the selection of the proper structural system (Naeam, 2003, p. 2). As a result, remaining fully operational through the SLEQ load is chosen as the desirable seismic performance objective for this research. To achieve this seismic objective, the evaluation criterion is to keep the IDR under a certain amount depending on the design site condition and the relevant building provision.

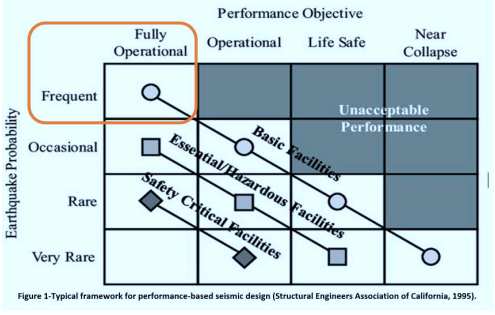


Figure 1-Typical framework for performance-based seismic design (Structural Engineers Association of California, 1995).

Figure 2
Typical framework for performance-based seismic design (Structural Engineers Association of California, 1995).

**b. Seismic Analysis Method.** In the PBSD method the selection of design criteria stated in the form of one or more performance objectives. However, different performance levels will require different design criteria to be applied to different design methods (BARROSO & et al, 2000, pp. 2-3). As a result, no single design method may satisfy all performance requirements. Furthermore, the desirable performances are evaluated by damage indicators while, no single damage indicator will provide all the information required to assess structural performance, especially at all performance objectives. Whereas the most advanced analytical, numerical and experimental methods should be used for seismic design of tall buildings, a balance between required accuracy and complexity of analysis should be considered, depending on the importance of a building and on the aim of the analysis (Fajfar, 2018, p. 2). In the previous section, the SLEQ has been chosen as a primary analysis load. The building responds to this load should be elastic, so the seismic design method should be a linear elastic method. The Equivalent Lateral Force (ELF) Analysis and the Response Spectrum (RS) Analysis are two seismic linear elastic analysis methods. Still, the difference is that one is static analysis, while the other is a dynamic analysis (Table 2). While the dynamic analysis method will give a more realistic load distribution and would consider the "higher-modes effect" (Charilaos & et al, 2013, pp. 417-420) (Guerrini, 2017, pp. 1-3); it is too complicated for the early stage of architectural design and schematic form-finding. On the other hand, a parametric based optimization design method will produce more than a hundred alternatives for any specific initial datasets; this makes the RS really time-consuming and inconvenient for the primary stage of architectural design. Instead, the preliminary seismic design of many buildings is normally based on ELF method obtained from seismic design guidelines and codes of practice (Chopra, 2017). This method has gained approval since regular buildings designed by this approach have, in general, performed acceptably in earthquakes (SEAOC, 1999, p. 120). Although this approach may not generally be precise for the seismic design of tall buildings, it would be enough for their primary analysis in the architecture design stage (Kazemi, Khoraskani, & et.al, 2018, p. 3). Since this research is going to propose a primarily seismic performance evaluation for the conceptual design phase, it will utilize the ELF method for seismic analysis of different alternatives.

Table 2
Division of different seismic analysis methods

| Linear Analysis | | Non-Linear Analysis | |
|---|---|---|---|
| Static | Dynamic | Static | Dynamic |
| Equivalent Static Method | Response Spectrum Method | Pushover Method | Time History Method |

### *Model Making; Parametric Design*

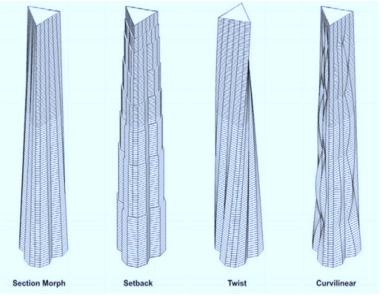


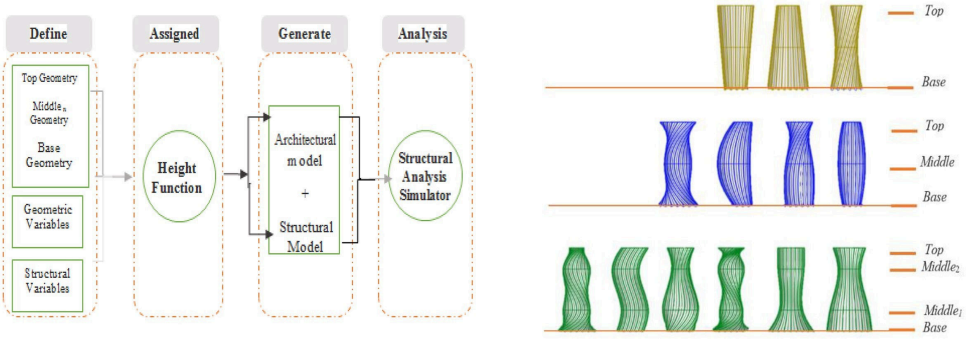

Figure 3
Parametric tall building form generation rule: initial geometries as the base and top plan and various vertical transformation functions (Park M. S., 2005).

In this phase, a tall building parametric model will be defined in which the form generating variables are sensitive to its seismic performance. Generally, a parametric model is designed by rules and constraints, which define different aspects of the building and their relationship to each other. According to (Park M. S., 2005) Generating a typical tall building with a parametric form is possible by following a simple technique: using two primary geometries as the base and top floor, one or multi-functions for vertical transformation and sets of variables to generate architectural form (e.g., story height, total height, number of stories, etc.) and its corresponding structural system (e.g., the number of columns, bays, bracing, etc.) (Figure 3). Using more primary geometry, for example, in the middle of the model, would result in more creative alternatives (Figure 4). Once the various parametric inputs have been set, the synthesis process is carried out to generate the initial geometry. However, since this research focuses on the regular forms based on seismic design definition, special care must be given to avoid any irregularity in defining the initial geometry both in defining variables itself and specifying their variation range. For this purpose it is necessary for architects to be familiar with the seismic design definitions and seismic architecture issues for selecting the initial parameters and their corresponded variation range; e.g., defining a various range for story height but constant for every floor through the height, would prevent soft floor irregularity (Arnold C. , 2006, p. 19). Additionally, since the building structure is generating along with architectural geometry at this stage, being aware of seismic architecture issues would help to avoid unfavorable effects of complex forms on the efficiency of the structural system even before any analysis; e.g., for a twisted tower, releasing the column from the twisting shape of the building or adding a counter-rotating column significantly reduce the torsional force (Arup, 2007, p. 447).

### *Solution-Assessment*

In this phase, the design alternatives embedded into the parametric model should be explored based on the performance evaluation criteria by using an optimization algorithm. Based on section A (Strategy-Definition phase), having minimum IDR would represent the desirable performance of a tall building against frequent earthquakes. However, minimizing IDR alone would deviate the optimization process from achieving the optimum seismic architectural form. This would happen because the lateral load resistance structure members are among the variables of the initial parametric model; therefore, when the optimization algorithm objectives minimizing the IDR, their size and number would increase rapidly and dominated the optimization process due to their high impact on reducing the IDR. Resultantly, the final alternative would have a substantial weighted structure which cannot be considered as an optimum in seismic design perspective. Furthermore, when it comes to tall buildings efficiency design, buildings' lateral structural weight plays a critical role on total building cost (Moon K. s., 2008, pp. 1-3) and has an important influence on sustainable design concepts (Felkner & et.al, 2019, pp. 1-2). As a result, both the IDR and the structure weight should be minimizing simultaneously. The first solution on this regard is to combine multiple criteria into a Single-object Optimization (SOO) problem (Cardoso & et.al, 2017, p. 257) i.e., defining a constraint for the optimization algorithm to keep IDR under a certain amount and combine it with another constraint to avoid going so far from that amount. This would result in generating

Figure 4
A typical tall building parametric modeling process. The greater the number of middle geometry leads to more complex and various forms(Authors).

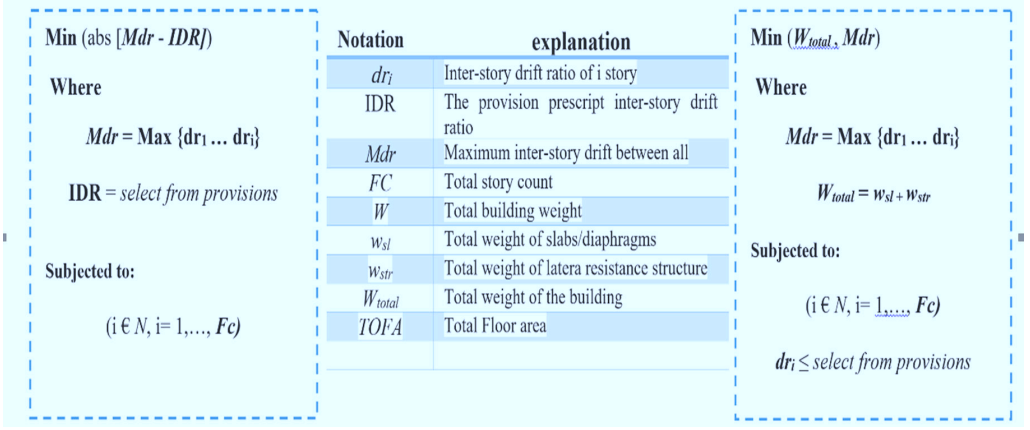



the most light-weighted alternatives that could satisfy the minimum IDR constrain. The other solution is to use Multi-Object Optimization (MOO) techniques and minimize both objects (the structure weight and the IDR) while using the maximum amount of IDR as the optimization constraint(Figure 5). Each of the optimization techniques has its advantages and disadvantages that have to be chosen based on the design feature (Wortmann & et.al, 2017, pp. 4-5).

## PROPOSING THE POD FRAMEWORK; TOWARD AN INNOVATIVE DESIG SOLUTION

A POD framework for the initial evaluation of tall building seismic performance in the conceptual phase of architectural design is proposed based on the three phases discussed earlier (Figure 6). This framework is capable of performing a primarily seismic analysis to evaluate the effect of a tall building form complexity on its seismic performance. According to the previous definition, the scope of the proposed framework is any tall building with a complex form, which is considered regular from a seismic de-

Figure 5
The SOO (left) and MOO (right) optimization problem definition



sign point of view. The three phases of the proposed framework are not linearly dependent as the second and the third phase will be performed in an iterative loop. The first phase, Strategy-Definition, defines the primarily seismic design criteria and performance evaluation factor. However, the numerical range of these criteria depends on the seismic design code of the tall building design region. Once the numerical ranges are defined, in the Model Making phase, the process starts with the preparation of a parametrically defined geometry model that represents the initial design intent. The set of parametric inputs includes the various design factors that directly influence the architectural form and the structural system, would be defined by the user. Once the various parametric inputs have been set, the synthesis process is carried out to generate the initial geometry. In the third phase, the Solution-Assessment, the initial geometry is subjected to a geometric modification process. The performance criteria guide the modification, and the optimization algorithm would implement the assessment based on the SOO or MOO problem definition. The optimization algorithm executes this modification as an iterative process until the best possible answer is achieved.

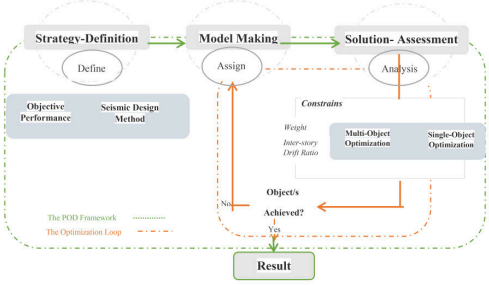
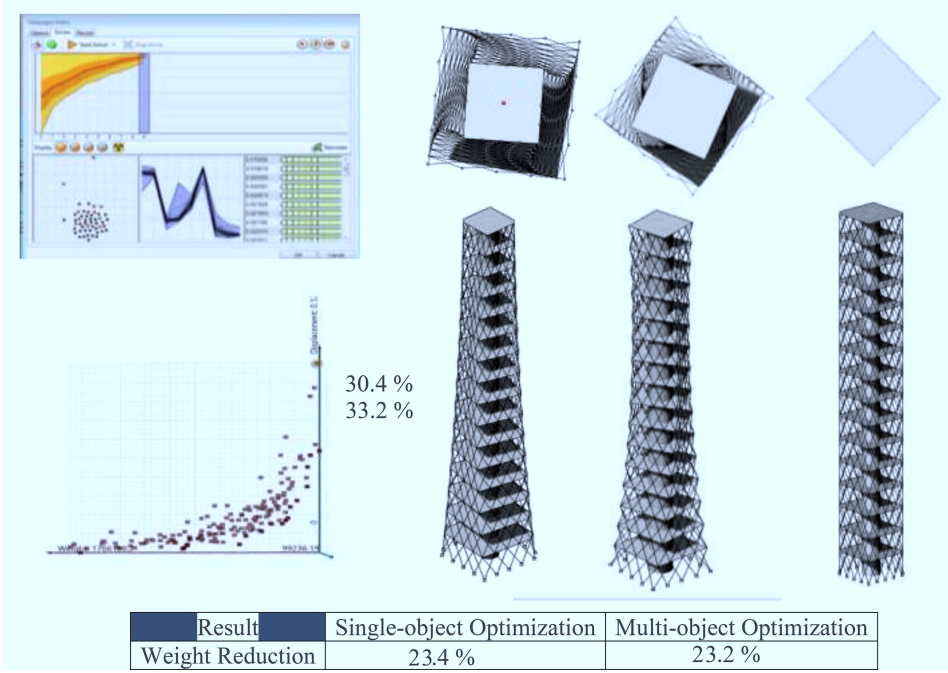



Figure 6
Performance-Oriented Framework for early form development of tall buildings from seismic architecture view(Authors).

## THE CASE STUDY: THE EFFECT OF REGULAR FORM COMPLIXCITY ON SEISMIC BEHAVIOR

The proposed framework is used to optimize a tall building with a complex form includes a combination of Taper and Twist. Rhinoceros, along with its graphical parametric algorithm editor Grasshopper, is used as a parametric design tool for generating an initial parametric model of architectural and structural forms. The Karamba3D used as the structural performance simulation program and the Genetic algorithm used as the optimization algorithm. The initial form has been derived from the primary base, middle, and top rectangle defined in XY plane with different attributes in Z-axis, and Loft is used as the vertical transformation function. Diagrid is chosen as the main lateral load resistance structure and the number of diagonals and the horizontal and vertical bracing spans are defined as structural variables. Taper and Twist are applied to the initial box-shape geometry by the variation of 0-45 degrees through its height. The seismic performance, design method, and the IDR constraint are defined based on (PEERc, 2010) and the calculation and application of ELF and the static linear analysis are done all based on (FEMA P-751, 2012). For the sake of comparison, the range of variations of all the alternative models are limited in order to generate alternative models with the same gross area and total height. Resultantly, the only changing weight which is calculated is the lateral structural weight. Generally, Taper has a favorable effect on building seismic performance while the impact of "Twist" is not linearly traceable. This is because "Taper" would decrease the height of the building's center of mass, thus increasing the lateral stiffness of the building, and consequently decreasing the IDR. Whereas, "Twist" affects the bracing inclination and their relative angle, which is favorable in some degrees, and not in some others. Therefore, it is not simple to predict the optimum seismic form of a tall building that has a combination of both. In the SOO approach, the optimization algorithm changes the form variables (both the architectural and the structural ones) based on the feedback of the SOO and MOO target objectives. Based on the SOO fitness-function, the optimization goal is to choose the alternative with minimum weight, and the IDR limitation is used as a constraint criterion that




| Result | Single-object Optimization | Multi-object Optimization |
|---|---|---|
| Weight Reduction | 23.4 % | 23.2 % |

Figure 7
The case study; Taper-Twisted tall building optimization based on seismic performance. from right to left: the initial geometry, the MOO result and the SOO result(Authors).

should not be violated. On the other hand, the MOO method results in a Pareto-front diagram of different alteration with different weights that lies within acceptable IDR range. The advantages are that this diagram makes it possible to see a trade-off between the form complexity and its seismic performance. Both optimization methods, however, result in a final alternative, which has about 12 % reduction in weight comparing to the initial box-form model while both remained in the acceptable IDR range(Figure7).

## CONCLUSION

The term "seismic architecture" has been used first by (Arnold & Reitherman, 1982), who state that the architectural decisions about form would dramatically affect the buildings' behavior during an earthquake. In the first place, this approach had a broad perspective of exploring all aspects of the interrelation between architectural form and seismic response and states that architects should be responsible for the effect of their decisions on building seismic performance. However, it gradually limited to the definition of regular and irregular form, and not much has been done on other aspects of this perspective in previous years. Today parametric based CAAD software with optimization techniques make architect capable of generating various infinite forms. Many of them may not include any of the irregularities mentioned in the provisions and thus considered as a regular form. Still, evaluating their seismic response and finding the tractable solution(s) for improving it, is challenging, especially by an architect. Furthermore, while the form has a much more sizable effect on the seismic performance of tall buildings, many of them have a complex form according to the needs of the project. Addressing this problem, this research focuses on proposing a performance-oriented framework for seismic performance evaluation of tall build-

ing forms in the early stage of form development in the architectural conceptual design phase. The process of defining this framework has been done in three phases which are not related linearly, as the second and the third phase will be performed in an iterative loop. The proposed framework is used to optimize a tall building with a complex form includes a combination of Taper and Twist with Diagrid structure. The optimization resulted in an alternative form with a 12 % reduction in weight compared to the initial box-form model while its IDR lies in the acceptable range. The novelty of this study is that it proves by example that even in a totally tall building with totally regular buildings, the architectural form has considerable effects on its seismic performance. Additionally, the proposed seismic POD framework is capable of providing the architects with qualitative insight and initial quantitative evaluation of the seismic performance of any regular-complex form during the conceptual design phase. This framework can be used as an assistant for architects in developing their tall buildings form while striking a balance between their decisions in architectural design and the impact of them on the seismic behavior of the building.

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# Translating Fengshui into algorithmic design

## *A digital tool to examine the impact of Fengshui on Siheyuan's layout*

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*In continuation of our previous work on the design principles of traditional Beijing Siheyuan courtyard housing and their implementation into computational algorithms, this paper investigates the impact of the Fengshui theory on its layout. In particular, we will present the development of a Grasshopper algorithm able to examine Siheyuan houses' fortune status according to their layout. We have verified the algorithm by using Siheyuan precedence from the ancient Beijing map and measuring surveys on extant buildings. Our findings highlight that most Siheyuan houses were designed to be auspicious even though other forces were working against*

**Keywords:** *Siheyuan, digital heritage, algorithmic design, Fengshui, Gongcheng Zuofa Zeli*

## INTRODUCTION

Courtyard housing was the most common dwelling type in ancient China. The Siheyuan, traditional Chinese courtyard housing type from Beijing, is a typical representative of traditional Chinese vernacular architecture. A typical Siheyuan consists of axially aligned courtyards symmetrically surrounded by individual buildings connected by orthogonally located corridors, walls, and gates, as illustrated in Figure 1.

When Beijing was rebuilt between the Yuan and Qing dynasty, Siheyuan became one of the most potent symbols of imperial rule. As the basic cell of ancient Beijing's urban texture, it embodied the rules of feudal society in its architectural form. Many studies such as by Ma (1999), Zhao (2013), and Lu and Wang (2013), have paid attention to its archetypal form in traditional feudal society.

After Liang and Chen's urban planning proposal to preserve historical Beijing city was rejected by the Beijing government in 1950, many Siheyuan houses were damaged or destroyed up to the present day. One of the consequences of this destruction is that current architects lack knowledge of its principles, thus their Siheyuan design projects are considered as fake. In support of the preservation and popularization of Siheyuan design knowledge, many studies re-introduced its design principles using historical records. For example, Ma (1999), and Lu and Wang (2013) comprehensively introduced forms of architectural components of traditional Siheyuan based on extant buildings and historical materials. Zhao (2013) studied tectonic methods of Siheyuan's architectural components by the understanding of ancient construction rules and interviews with successors of ancient craftsmen.

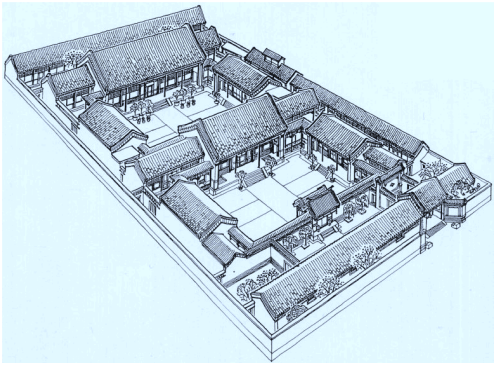


Figure 1
Beijing Siheyuan, after Ma, 1999.

On the other hand, three computational approaches created by western scholars, shape grammar (Stiny, 2006), space syntax (Hillier and Hanson, 1984) and pattern language (Alexander et al., 1977) were employed in Chinese courtyard housing studies to explore its design logic. Chiou and Krishnamurti (1995a) developed the grammar of vernacular dwellings in Taiwan, a branch of Chinese courtyard housing, which enhanced the understanding of its design. Huang et al. (2018) analysed the spatial configuration of an ideal archetypal model using DepthX Map and advised to inherit Siheyuan's cultural connotations in contemporary housing design. Liu (2019) studied the composition of walls and rooms on Siheyuan examples recorded on the historical map Jingcheng Qianlong Quantu (1750) by categorizing types of courtyards. Their classifications of patterns of courtyards and rooms revealed the design constraints underlying practice.

In ancient Chinese philosophy, the cosmic aspect of nature is the essence of everything. Therefore, ancient Chinese knowledge about it was applied to many subjects by analogy. Fengshui (cloud and water) is geomancy based on this analogy to guide adapting cities and buildings to achieve harmony with nature. There are two branches of Fengshui theory: *Xing Shi* (observing context) and *Li Qi* (regulating vital energy). The *Xing Shi* helps geomancers to select an auspicious site and the *Li Qi* based on the concept of "cosmic resonance" helps craftsmen and householders predict and select auspicious orientations, qualitative space, and dimensions of rooms in the design process.

Even though there are a great number of studies on Siheyuan design, the important cultural factor, Fengshui, has rarely been explored for its influence on Siheyuan's architectural form. In the context of Taiwanese vernacular dwellings, Chiou and Krishnamurti (1995b) investigated the method from *Li Qi* to determine the fortunate dimension of a building using the ancient measuring ruler *Lu Ban Chi* and interpreted it in an algorithmic format. Later, they (1997) also introduced applications of *Li Qi* in finding fortunate orientations of a site and auspicious dates to start building construction and implemented it in computers. Meanwhile, Wang et al. (2019) created an interactive tool to parametrically design Siheyuan following Fengshui, in which assessment rules of the fortune of Siheyuan site context from *Xing Shi* were embedded. Although this research made passing reference to the principles of Fengshui on architectural design, the implementation of Fengshui in the Siheyuan's form in practice has rarely been investigated. This study aims to explore how principles from Fengshui constrain Siheyuan design as well as investigate how Fengshui harmonizes with other cultural forces to influence Siheyuan's form in practice, through the development of an algorithmic tool. In particular, our main aim addresses the three research questions:

1. How do Fengshui principles influence Siheyuan design?
2. How can these principles be implemented into algorithmic design and be applied as an interactive tool for examining the fortune of a Siheyuan house?
3. Were these principles being applied in traditional Siheyuan design practice?

To answer these questions, we have first studied the Fengshui theory based on historical material and interviews with Fengshui geomancers to clarify the original principles relating to Siheyuan design. We

have then analyzed the mathematical logic underlying its principles to produce an algorithm using the *Grasshopper* visual scripting platform. Finally, we have employed this algorithm as a tool to examine the fortune of historical Siheyuan cases, whose corpus has derived from measuring surveys of extant Siheyuan examples and documented historical examples.

## MATERIALS AND METHODS

### *Source of rules*

As stated above, *Xing Shi* is used to finding proper sites for building construction while *Li Qi* is to find fortunate orientation, size ratio, and the dimension of buildings. *Li Qi* dominantly shapes the form of Siheyuan. Principles in Fengshui constraining orientation, size ratio, and dimensions of buildings were selected to study, which were originally recorded in historical books such as *Dili Huitu Wu Jue* (*Five Tips For Geographic Mapping*, Zhao, 1785/2011a), *Bai Zhai Ming Jing* (*Eight Mansions Bright Mirror*, Gu, 1790/2010), *Yang Zhai San Yao* (*Three Essences of Positive Houses*, Zhao, 1786/2011b).

### *Methods*

Many previous architectural Fengshui studies, as noted, centred on its metaphysical and anthropological aspects but neglected to examine its influence on its building form. However, Chiou and Krishnamurti (1997) illustrated the potential to solve this problem by using an algorithm to interpret the application method of Fengshui. Taking this idea further we uncover Fengshui's influence with a digital interactive tool developed in *Rhino/Grasshopper*. Since Fengshui influences buildings in orientation, size ratio, and dimension, we were able to test our algorithm by entering data of historical Siheyuan examples into the tool to generate results shaped by Fengshui principles and then compare them with corresponding historical ones.

## ANALYSIS OF FENGSHUI PRINCIPLES

Fengshui geomancers supposed a kind of mysterious energy called *Qi* flows in the air in the form of invisible gas. This gas brings good fortune to people. *Li Qi* is the method to steer this energy. In the case of Siheyuan, the proper size ratios and function of rooms can store this energy in the housing space.

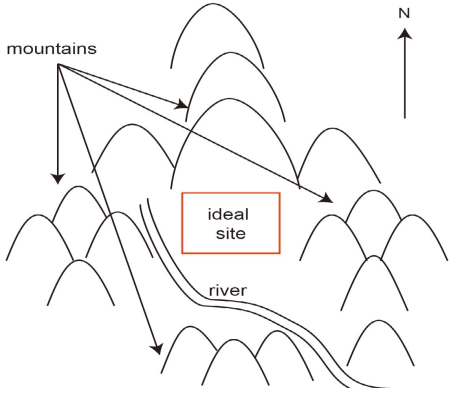



Figure 2
The ideal environmental context from Xing Shi.

### *Room Orientation*

As shown in Figure 2, *Xing Shi* gives an ideal environmental context in Fengshui for a building's or a city's site. The site should be surrounded by hills and mountains (the highest and largest mountains at its north side), located on the smooth ground with its main elevation facing south and a river crossing its front area. However, as Beijing's urban area had been subdivided into an urban grid system, it is almost impossible to find this ideal context. Referring to the original considerations of Fengshui and regarding the urban planning of ancient Beijing, we simplified the principles into two main constraints: 'being within the auspicious degree ranges of orientation' or 'facing an adjacent street or alley'. The simplest way to find the auspicious degree is to use a Fengshui compass, which averagely divides a 2D plane into 24 sections (called '24 mountains') by 15 degrees and additionally divides each section into 5 subsections by 3 degrees, as shown in Figure 3. Degrees located within each second and fourth subsection are

defined as auspicious orientation. The first constraint requires the elevation of the primary room of each courtyard in Siheyuan orientated within the range of auspicious degrees. The second requires it facing an adjacent street or alley, but there are two exceptions. If the adjacent street or alley exists on the north, primary rooms face the opposite direction. If adjacent streets or alleys exist on multiple sides, there is a priority sequence of determination of primary rooms orientation: south> east> west> north.

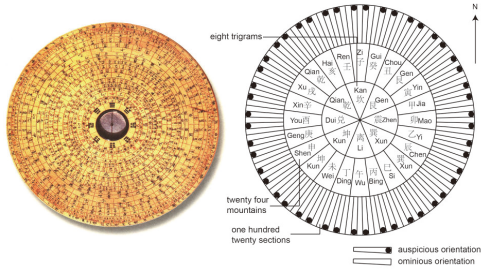



Figure 3
A Fengshui compass and fortunate orientation.

| 乾 Qian | 坎 Kan | 艮 Gen |
|---|---|---|
| 兑 Dui | | 震 Zhen |
| 坤 Kun | 离 Li | 巽 Xun |

eight trigrams

| | | |
|---|---|---|
| 6 | 1 | 8 |
| 7 | 5 | 3 |
| 2 | 9 | 4 |

numbers

| | | |
|---|---|---|
| metal | water | earth |
| metal | earth | wood |
| earth | fire | wood |

five elements

| | | |
|---|---|---|
| white | white | white |
| red | yellow | dark green |
| black | purple | green |

colors

N

Figure 4
Area attribute.

## *Room Size Ratios*

Size ratios of rooms in a courtyard are various. In Fengshui, there are many methods to identify room size ratios., such as *Da You Nian* (big tour calendar), *Chuan Gong Jiu Xing* (crossing courtyard nine stars), *Fen Fang Jie Lu* (dividing rooms and intercepting paths), whose logics are the same but the determination of parameters or the applicable types of Siheyuan vary. Siheyuan is classified into three types: one-courtyard Siheyuan, Siheyuan with multiple courtyards aligned in the depth direction, Siheyuan with multiple courtyards aligned orthogonally. Here we propose the method of one courtyard Siheyuan and then supplement the differences between it and the method of the other two Siheyuan types.

For one-courtyard Siheyuan:

1. Divide the courtyard of the Siheyuan into nine areas with a three-by-three grid, and then allocate the eight trigrams (*Bagua*) to the eight boundary areas (the central area is left as empty) according to its orientation. The allocation of each trigram corresponding to the eight boundary areas are: east-*zhen*, southeast-*xun*, south-*li*, southwest-*kun*, west-*dui*, northwest-*qian*, north-*kan*, northeast-*gen*. The principle to allocate the eight trigrams to the eight boundary areas comes from the identification of attribute of each area recorded in *Luo Shu* (*Decussation Rivers Book*). The attribute of an area includes one of eight trigrams, one of the five elements (*Wuxing*), a number between one and nine, and one of seven colours, which depends on the area's location, as shown in Figure 4.
2. Identify the area of fortune origin. The area of fortune origin is where the centre point of the keyspace locates. Either the entry gate or the primary room could be the keyspace. It is important to state to the selection of the type of the keyspace (the entry gate or the primary room).
3. Assign the 'nine stars (*Jiu Xing*)' to eight trigrams according to the location of the area of fortune origin. In Fengshui, the seven stars of the Great Bear constellation and two nearby stars, called 'nine stars', were analogized with meanings of fortune. Each of the nine stars is assigned with fortune, as shown in Table 1. Each of the eight boundary areas is associated with one of the nine stars. Once the area of fortune origin is identified, each area's associating star(s) is(are) determined. Geomancers created a pithy formula to represent the eight results corresponding to the eight each of the eight areas as being the area of fortune origin. The eight results are shown in Figure 5.
4. Calculate the fortune of each area by the principles 'five elements produce and destroy'. The

concept of 'five elements' comes from *Luo Shu*, in which each of the eight trigrams attributes an element within the five: metal, wood, water, fire, and earth. The correspondence between trigrams and elements are shown in Figure 4. Each star of the nine stars is assigned with fortune and also one of the five elements as an attribute, shown in Table 1. Between every two elements, there is a 'destructive' or 'productive' relation as shown in Figure 6. The way for identifying the fortune of an area is using the element of the star assigned in this area to compute with the element of the trigram of the area of fortune origin. For each area assigned with an auspicious star, a) if the element of the star is in 'destroy' relation with the element of the trigram, the area is lesser auspicious, and b) if the element of the star is in 'produce' relation with the element of the trigram or they are the same, the area is greater auspicious. For each area assigned with an ominous star, a) if the element of the star is in 'destructive' relation with the element of the trigram, the area is lesser ominous, and b) if the element of the star is in 'productive' relation with the element of the trigram or they are the same, the area is greater ominous. For the *Zuofu* star and *Youbi* star, the area they belong to is always least auspicious.

For Siheyuan with multiple courtyards aligned in the depth direction, there are four differences:

- Step 1 is applied to each courtyard of the Siheyuan separately,
- Only the entry gate could be the keyspace.
- The trigram and the star of each of eight boundary areas in the first courtyard are identified in the way the same as it is for one-courtyard Siheyuan, and this pattern is applied to all courtyards except the mid back area.
- Assign the corresponding star of the mid-front area of the first courtyard and then assign the star of the mid-back area of each courtyard sequentially according to the order of production of the '*Na-tone* five elements', as illustrated in Figure 7.

Figure 5
Eight results of assigning the nine stars to eight trigrams.

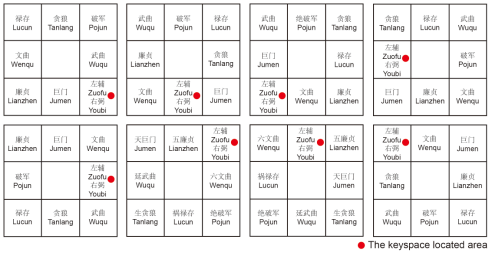



Table 1
Correspondence between the nine stars, five elements, and their fortune.

| Nine Stars | 贪狼 Tanlang | 巨门 Jumen | 禄存 Lucun | 文曲 Wenqu | 廉贞 Lianzhen | 武曲 Wuqu | 破军 Pojun | 左辅 Zuofu | 右弼 Youbi |
|---|---|---|---|---|---|---|---|---|---|
| Five Elements | wood | earth | earth | water | fire | metal | metal | water | wood |
| Fortune | ● | ● | ● | ● | ● | ● | ● | ● | |

● auspicious ● ominious

Figure 6
Five elements produce and destroy principles

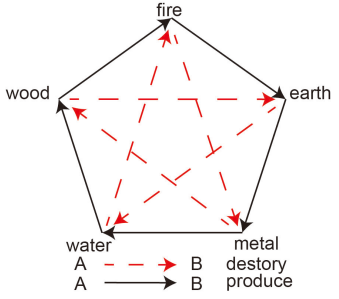
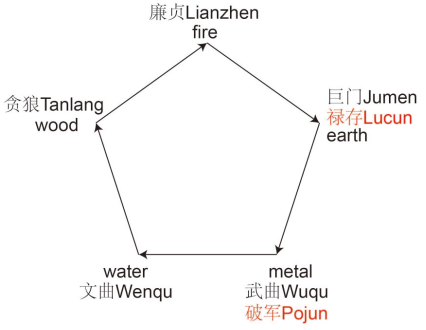



Figure 7
Order of Na-tone five elements. (the stars Pojun and Lucun only exist in the mid area of the first courtyard.)



For Siheyuan types with multiple courtyards aligned orthogonally: each courtyard could be seen as an individual Siheyuan to compute.

The fortune of area forces size ratios and functions of rooms constructed in each area. Normally, rooms in auspicious areas are large while in ominous areas are small. Two examples of the process for a one-courtyard Siheyuan and a Siheyuan with five courtyards aligned in the depth direction are illustrated in Figure 8.

### *Room Dimensions*

The 'Pressing White Ruler Method' from Fengshui identifies the fortune of dimension, which filters the ranges of dimensions by Lu Ban rulers. In this method, there are two principles, the *Chi Bai* (feet white) and the *Cun Bai* (inch white) constraining the dimensions in parallel. Since only the *Chi Bai* are applied to dwellings normally and most Siheyuans are dwellings, we analysed the *Chi Bai* principle, which consists of five steps:

1. Identify the orientation of the room's door within the 24 mountains of a compass (figure 3) and then find its opposite section on the compass.
2. Use the 'earth mother selecting first' (*Di Mu Na Jia*) principle to identify the trigram of the opposite section in the eight trigrams. The correspondence between the twenty-four mountains and the eight trigrams are shown in table 2.
3. Find the corresponding colour and number of the trigram in Luo Shu and then use it as the first range on a Lu Ban ruler. The correspondence between trigrams and numbers is shown in table 3. This correspondence has two variations: the heaven trigram and the earth trigram. The heaven trigram is to determine fortune dimensions in the vertical direction- the height of the building, and the earth trigram is to determine fortune dimensions in horizontal direction- width and depth of the building.
4. Identify the sequence of numbers. Based on the first number to assign each range's number re-

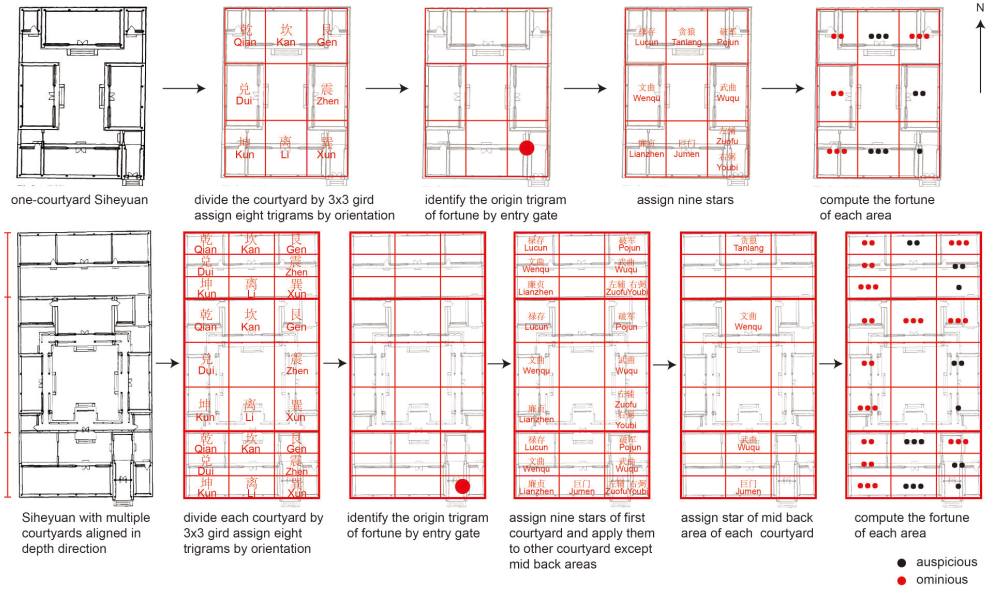



Figure 8
Two examples of the process of computing room size ratios of areas.

peatedly on the Lu Ban ruler in numerical order from Luo Shu, as illustrated in Figure 4. In the assignment, the heaven trigram excludes number 1 and the earth trigram excludes number 9. 1 range= 3.2 centimetres. Each number indicates its fortune.

5. Use each auspicious colour's corresponding element in the five elements to compute with the element identified in 24 mountains by the building's orientation (Figure 3) according to the principles "five elements produce and destroy". If the two elements are the same or in 'productive' relation, the colour's corresponding range is identified as auspicious, otherwise, as ominous.

Table 2
The correspondence first number of each trigram in the eight trigrams.

| number | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|
| the heaven trigram | | 坎Kan | 坤Kun | 乾Qian | 巽Xun | 艮Gen | 震Zhen | 离Li | 兌Dui |
| the earth trigram | 乾Qian | 离Li | 震Zhen | 兌Dui | 坎Kan | 坤Kun | 巽Xun | 艮Gen | |

Table 3
The correspondence between the twenty-four mountains and the eight trigrams in the "earth mother selecting first" method.

| eight trigrams | 乾Qian | 坎Kan | 艮Gen | 兌Dui | 震Zhen | 巽Xun | 离Li | 坤Kun |
|---|---|---|---|---|---|---|---|---|
| twenty four montains | 乾Qian<br>甲Jia | 癸Gui | 丙Bing<br>申Shen<br>子Zi<br>辰Chen<br>艮Gen | 丁Ding<br>巳Si<br>酉You<br>丑Chou | 庚Geng<br>亥Hai<br>卯Mao<br>未Wei | 辛Xin<br>巽Xun | 壬Ren<br>寅Yin<br>午Wu<br>戌Xu | 乙Yi<br>坤Kun |

## DEVELOPING THE ALGORITHM

Based on the analysis explained above, we identified four key input parameters for *Grasshopper* to determine Siheyuan houses' fortune. They are: for the orientation of the Siheyuan house, a) the location of the adjacent street or alley, for the rooms size ratios in a courtyard, b) the selection of the type of the keyspace and c) the location of the keyspace, and for the dimension of each room, d) the orientation of the room. Accordingly, we produced an interactive *Grasshopper* script for the implementation of the algorithm to identify the fortune of the house's orientation, room size ratios, and room dimensions. The workflow is illustrated in Figure 9.

To implement the algorithm in *Grasshopper*, the plan of a Siheyuan and site context is imported. In our *Grasshopper* script, streets or alleys of the Siheyuan are identified by being collected by *Curve* components. The surrounding area of a Siheyuan site is identified and divided into four parts (north, south, east, and west) and collected by *Curve* components to find adjacent streets or alleys. The selection of the type of the keyspace is indicated by a 'silder' component, whose values are to be inputted. The plan of the keyspace is identified by a 'curve' component to find their central positions and then identify their locations within the 3x3 gird. The orientation of each room is identified by a Vector 2Pt component, whose orientation is from the central point of the room to the central point of the line indicating as the room's front elevation on the plan.

## VERIFICATION

To verify whether Fengshui was used in Siheyuan design to obtain auspicious patterns, we used our tool to identify the fortune of Siheyuan examples by deriving the value of parameters from the precedents and then examining whether they are auspicious or not.

The Qianlong capital map (1750) presents all the buildings of Beijing at a scale of 1: 650, including thousands of Siheyuan houses. Duan (2016) organized measured surveys on existing Siheyuan examples. We selected two examples(left two in Figure 10) from the map and another two from Duan's surveys(right two in Figure 10), which are the most common types according to Ma (1999), Zhao (2013), Lu and Wang (2013), and Wang and Song (2012). However, the map and the measuring surveys cannot be used for verifying rooms' dimensions as well as we would like. Alternatively, examples of individual buildings recorded in *Gongcheng Zuofa Zeli* were used to replace rooms in the selected examples since they are described with detailed dimensions. The individual buildings in this manual have been drawn by Liang (2006), who translated texts in the manual into architectural drawings with detailed dimensions noted. We assumed the dimensions of the primary rooms of our selected examples are the same as in

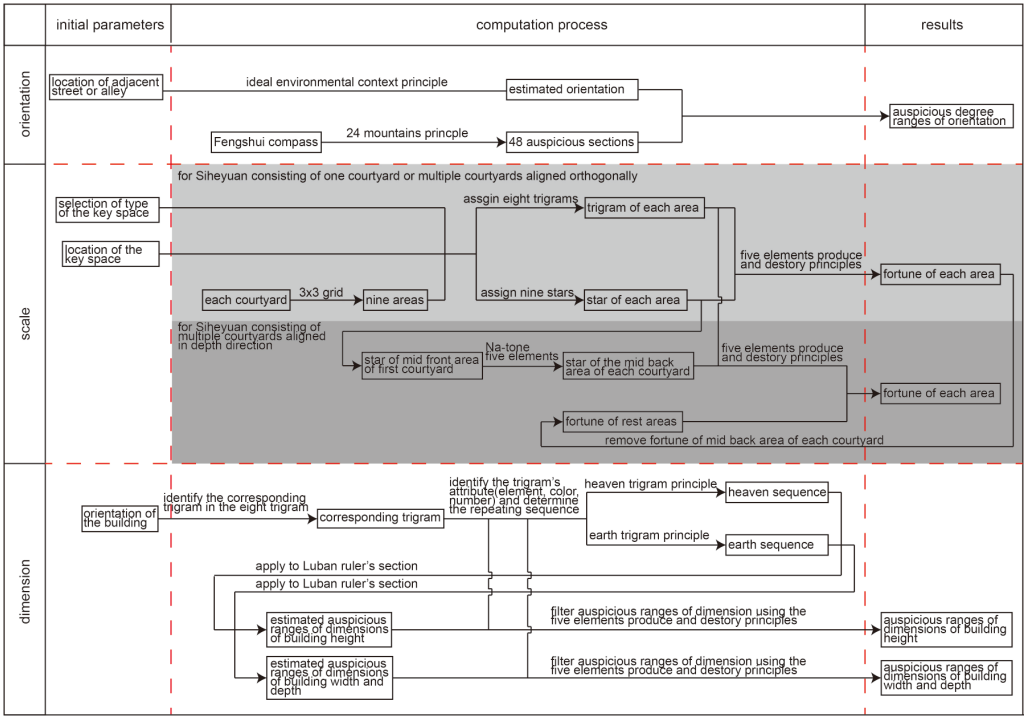



Figure 9
The workflow of Fengshui principles translated into a Grasshopper script

Liang's drawings. To be consistent with the Siheyuan rooms, a building given by Liang (2006) was modified by reducing the number of bays in the front view from five to three (in Figure 11) and then used as a primary room for verification. Figure 10 shows how our models assessed the fortune of our examples.

## DISCUSSION AND CONCLUSION

The results of the verification of four selected examples confirmed the Fengshui principles since they are mostly auspicious. We noted that other influence, more important than Fengshui, are also at work. For this reason, even the most common types, which are the closest to Siheyuan's ideal prototype, did not completely follow Fengshui to create auspicious patterns. For example, Confucianism and Taoism constrain rooms in a courtyard to be axial, and feudalism and clan constrain the size ratios of rooms in a courtyard in the sequence: primary room> east secondary room= west secondary> primary east wing room= primary west wing room> secondary east wing room= secondary west room. This constraint of room size ratio is more dominant than the one from Fengshui, so it can be easily observed that most Siheyuan houses follow this pattern. Meanwhile, to make Siheyuan conform to Fengshui, craftsmen would slightly change the room sizes to ensure size ratios of rooms are in auspicious patterns, which is hard to prove without conducting a measuring survey. This is the reason why, in many Siheyuan examples, the east wing room is slightly larger than the west wing room within a courtyard. Another exam-

Figure 10
Verification of four examples.

ple is the simplification of the *Cun Bai* method. The rules in *Gongcheng Zuofa Zeli* and consideration of material consumption constrained the available dimensions of a room in limited ranges. The constraint deriving from Fengshui dictates additionally limited ranges for room dimensions, but the ranges of each room may vary because it is a variable parameter for each room of a Siheyuan. This variability of room dimensions results in difficulty in building construction. However, in many cases, the limited ranges of room dimensions constrained by Fengshui are unified by simplification of the *Cun Bai* method. As a result of the simplification, instead of using the orientation of a room as the parameter to conduct the com-

plex calculation, the *Lu Ban* ruler, which consists of 9 units marked by their fortune type, is directly used to find auspicious dimensions of a building in practice. We infer this simplification is to solve the difficulty in building construction since it unified limited ranges of room dimensions constrained by Fengshui.

Figure 11
The dimensions of a building example applied in Siheyuan as primary rooms. After Liang, 2006.

There are two limitations to our study. First, for the verification of room dimensions, we have used ideal examples of buildings with constant values of dimensions according to *Gongcheng Zuofa Zeli*, but an individual building's dimensions could vary in practice, which may lead to errors of verification of room dimensions. Second, in this study, we only verified the most common Siheyuan types rather than all variations, whose Fengshui assessment results might possibly be different. Further research is needed to verify if Fengshui applies to these variants.

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# D2.T10.S1. ROBOTIC TECTONICS, AUTOMATION AND INTERACTION

# Spatial Timber Assembly

## *Robotically Fabricated Reciprocal Frame Wall*

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*Though highly robust and economical, traditional lamella and reciprocal structural systems cannot adapt to surfaces with complex double curvature; as the timber members are standardized with no variation. Recent research has explored the use of computation for design, structural optimization, and use of robotic systems for the automated fabrication of timber joints. The disconnection between fabrication and assembly makes the construction of non-uniform double-curved reciprocal frames challenging, due to the required precise placement of discrete members with compound angle butt joints. This project investigates the use of robotic fabrication to cut and assemble a timber reciprocal frame assembly. A computational model was created to generate the double-curved reciprocal frame geometry. Within this computational framework, joint analysis, fabrication, and assembly were monitored and adjusted to meet limiting factors. An industrial robot was implemented as a bridge between the computational model and the physical construction. This paper presents a number of novel computational and robotic fabrication techniques in designing, cutting, and positioning. These techniques were explored through the robotic fabrication and assembly of a demonstrator - a double-curved reciprocal frame wall.*

**Keywords:** *Robotic Fabrication, Reciprocal Frame, Prototyping*

## INTRODUCTION

### *History - Reciprocal Frame and the Lamella System*

Reciprocal frame structures, also known as nexorades, consist of short linear structural elements, with nodes offset along the centerline vector of an adjacent member in the system, generating a mutually supporting structural network (Figure 3). As a result, each connection point only involves two structural members, making it easy to assemble. The construction of reciprocal structures can be traced back to medieval times, when timber shortage required efficient use of material. Although the reciprocal system lacks structural redundancy (Douthe et al. 2009), its high malleability and efficient use of material have attracted growing interests among architects and engineers. Using computation and digital fabrication tools, contemporary research aims to

expand on the geometric adaptability of reciprocal frames. Reciprocal frames were notably documented in Leonardo da Vinci's sketches in 'Codex Atlanticus', where da Vinci explored various reciprocal patterns and uses (Thönnissen, 2015). In 1921, the lamella system was invented by German engineer Fredrick Zollinger (Zollinger, 1924), based on a similar set of rules to utilize short structural members for roof construction for houses, barns, hangers and other storage facilities, most of which follow symmetrical forms such as barrel vault and domes.

### *Previous Research in Reciprocal Frame Structures*

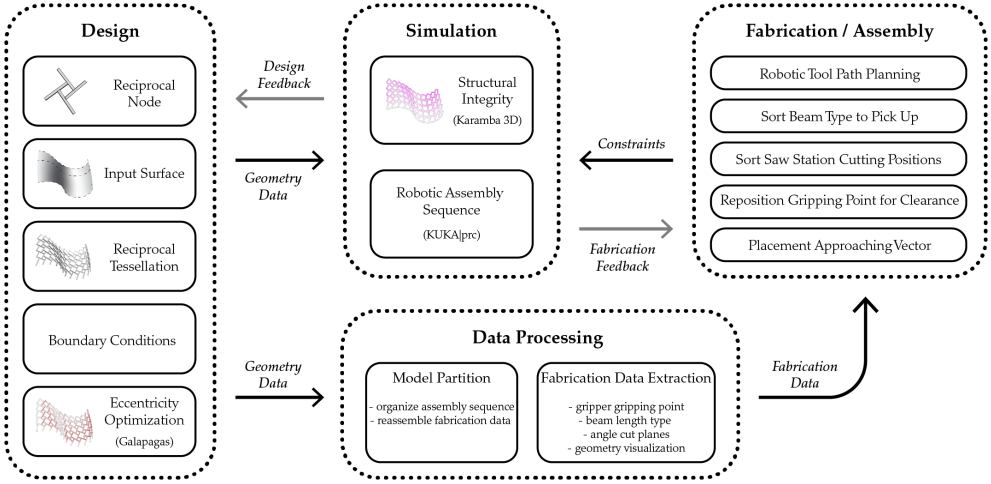
While most architectural applications of reciprocal frames are in simple symmetrical forms, the reciprocal frames built in the academic research settings are often non-uniform and cater towards cultivating students' hands on skills. Recent development on reciprocal frames was driven by the use of computation design methods from form-finding to digital fabrication. One of the most notable recent examples was the shell-nexorade pavilion by Romain Mesnil et al. (2018) from ThinkShell at the Laboratoire Navier, Ecole des Ponts ParisTech. Form-finding and robotic fabrication was used in this research. Their fabrication method employed a multi-robotic setup for milling the timber beams and panels. With 102 beams and 48 plywood panels, the pavilion was assembled on site without the use of robotics for positioning and fixing. On the other hand, research on spatial assembly has been conducted by Gramazio Kohler Research at the ETH Zürich (Eversmann et al. 2017; Kohlhammer et al. 2017; Parascho et al 2017; Adel et al. 2018). These research projects aimed to streamline the fabrication and assembly process to create large prefabricated modules from a series of discrete small pieces. This process preserves the element's identity information throughout fabrication and assembly, making building complex spatial structures less labour intensive. The use of structural reciprocity in their research was employed to resolve complex connections between small sized materials, which the robots were capable of processing.

### *Robotic Spatial Assembly of Reciprocal Timber Frames*

The research presented here builds upon this recent research by integrating fabrication and robotic assembly, and extending the capabilities of fabrication and construction of doubly-curved reciprocal lattice structures. This paper discusses the processes involved in making a reciprocal lattice wall prototype. The overall workflow (Figure 1) outlines the four modules of the process: design, simulation, data processing and fabrication. The design module consists of geometry design, control and optimization; this module outputs geometry information for simulation and data processing. The simulation module takes input from both the design and the fabrication module constraints and provides output feedback for design adjustment and fabrication setup. The geometry data is processed to extract key information, such as gripping points and cut planes, and package the data for the fabrication procedure. The fabrication module translates the data into physical movement of the robotic arm; this process involves picking, cutting and placing material following a prescribed sequence. It is capable of making individual adjustments to accommodate fabrication needs for unusual beam geometries.

In the Method section, a computational approach is presented for the generation of non-uniform reciprocal frame structures for robotic fabrication. This novel geometric generation method is then coupled with structural simulation and geometric eccentricity analysis. In the Fabrication section, the robotic cell and tooling approach is presented. Through analysis of the computational model, fabrication tools and systems were designed to meet the limiting geometric factors presented in the Method section. We conclude by discussing the future potentials for the development of non-uniform construction of reciprocal frame systems.

Figure 1
The overall workflow of our spatial assembly of reciprocal lattice structure.




## METHODS

This section contains a detailed description of the geometry development for surface subdivision for reciprocal frame generation. The focus was placed upon creating a simple quadrilateral reciprocal tessellated double-curved lattice with butt T-joints. In order for the structure to be buildable, the geometry was optimized to reduce eccentricity. This procedure ensured each connection point meets the minimum requirement for mechanical attachment. The reorganized geometry data was then simulated in a virtual environment to establish a collision free construction process.

### *Geometry Generation*

Contemporary research (Thönnissen 2014, Mesnil et al. 2018, Apolinaskar 2018) utilizes mesh tessellation to generate reciprocal patterns, allowing other operations such as form-finding and structural optimization. The research method presented here, however, used UV division of NURBS surfaces, a more common method among architects. The final reciprocal lattice prototype employed a single direction quadrilateral reciprocal pattern which was created with the following steps (Figure 2):

1. A double-curved surface was created by lofting three curves with different curvature.
2. This input surface was then subdivided in U and V directions. The minimum spacing was based on fabrication requirements, in this case, the width of the gripper.
3. A reciprocal pattern was created through the rotation of UV grid segments around their respective midpoints, normal to the input surface. Each segment represented the centreline of an individual beam.
4. The beam dimensions for the demonstrator were approximately 44mm by 33mm.The four sides of a rectangular beam was created by offsetting four planes around its centre line. The ends of the beam were cut off by the side of two adjacent crossing beams. Therefore, the compound end plane of the beam was one of the side planes of the adjacent crossing beam. Using plane to plane intersection lines, a solid beam geometry was created by lofting the intersection lines on both ends of the beam.

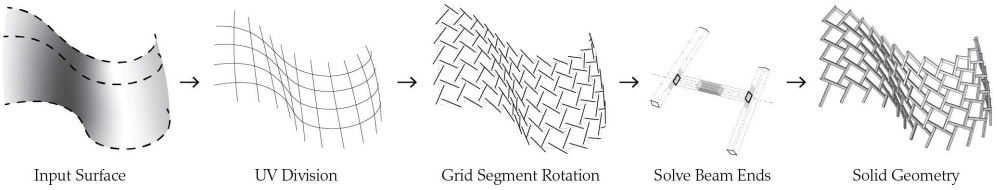



Figure 2
Reciprocal geometries were generated through tessellation of a double-curved surface.

## *Eccentricity Analysis*

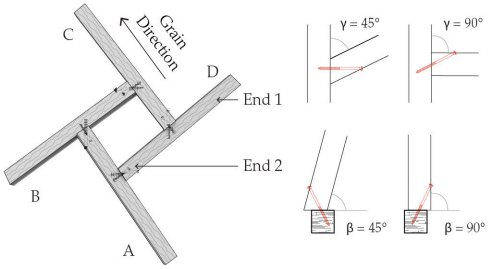



Figure 3
A reciprocal node where End 2 of D is supported by A, and End 2 of A is supported by B and so on (Baverel 2000). The logic repeats with End 1 supported by a member in another node. A minimum of two screws at each connection point was required for secure attachment. The zoomed in details illustrate the fastening technique we used in two scenarios, viewing from two different angles.

Eccentricity is defined as the distance between the axes of two attaching members (Mesnil et al, 2018). With the intention of using butt T-joints, a mechanical fastening method with wood screws was used in this research (Figure 3). A minimum of two screws at each connection point was required for secure attachment. This joining method required an adequate amount of contact area between the two joining beams. As the result of using a doubly-curved surface and a reciprocal-frame pattern, the eccentricity among beams would always be greater than zero. Therefore, the following steps were employed to minimize the eccentricity (Figure 4):

1. The collection of beams were divided into two groups of non intersecting beams. The positions of the two groups could be adjusted along each beam's surface normal vectors (refer to Geometry Generation) based on the average distance of the four connecting points at each beam. This method redistributed the eccentricity of a joint to other neighbouring joints.
2. The rotation of the beam (equivalent to the engagement length) could also control the eccentricity: the less the rotation, the less the eccentricity. As a result, the eccentricity could be reduced by locating an attractor point at the location of high eccentricity to reduce pattern rotations.
3. Lastly, the geometry of the input surface was another influencing factor. High curvature regions of the input surface typically results in high eccentricity. Adjustment was made to reduce surface curvature.

Genetic algorithm, Galapagos, was used to solve for the minimum eccentricity using the combination of the first two techniques to produce the final geometry for the demonstrator. A total of five genomes were used: the adjustment factors for the two groups of non-intersecting beams and the location of the attractor. 160 generations with a population of 50 each was computed, and the eccentricity was reduced from the original 40mm down to 28mm.

## *Simulation*

Two simulations were conducted: one to evaluate the structural integrity of the reciprocal geometry, the other was the robotic path planning. Based on the simulation feedback, the design of input surface, robotic routine, and placement of geometry on the build platform were adjusted.

Figure 4
Steps were taken to reduce the eccentricity in order to create enough contact area at joints.

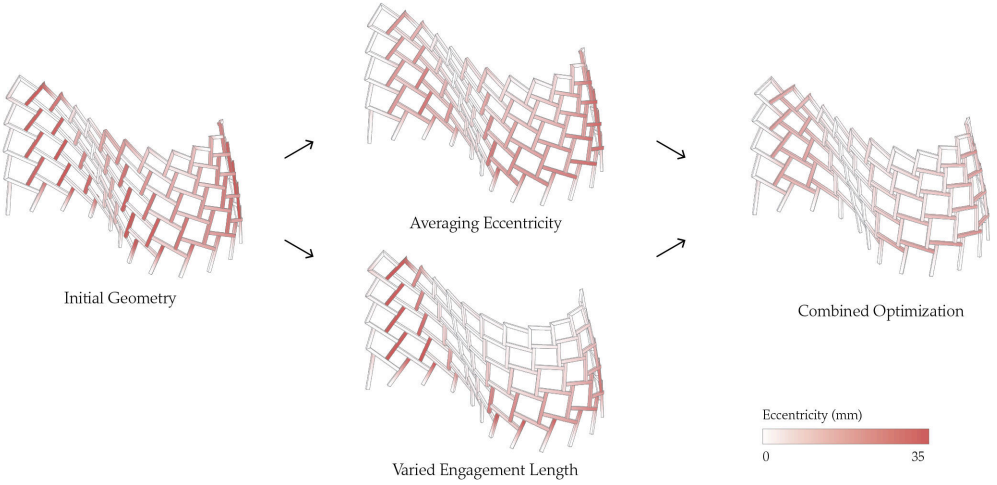
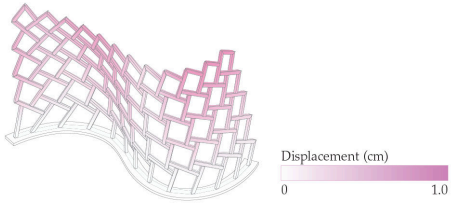



Figure 5
Structural simulation was done using Karamba 3D.




For the structural simulation, Karamba 3D plugin was used. Besides the gravity load, two point loads of 330N each were exerted on the two concave sides of the prototype lattice to simulate observers leaning against it. Wood material with Young's modulus of 1050 kN/sq.cm was used, while the base of the lattice was presumed to be fixed to the ground with rigid joints. The simulation indicated the prototype would have a maximum of displacement around 0.75cm at the top (Figure 5). The structural simulation provided feedback for design adjustment.

The fabrication and assembly processes were simulated within the Rhino Grasshopper environment using the KUKA|prc plugin, which writes KRL commands for robot controllers. The fabrication data, such as gripping point, beam length type, cut planes and sequence were extracted from the geometry model and packaged into individual beam units. The script simulated the robotic movement throughout while highlighting potential collisions; it evaluated the design of fabrication procedures. This feedback was used to improve the fabrication process. Mitigation for collisions include: repositioning structure on the build platform, shifting gripper gripping points, changing cutting positions, regripping between cutting and placing, adding or adjusting safe planes between steps, as well as adjusting placement approaching vectors. The final fabrication and assembly procedure singled out special scenarios such as short beams, special cut angles, etc. to apply above mentioned additional mitigation measures; approximately 36% of beams in the prototype required fabrication adjustment.

## FABRICATION SYSTEM AND TOOLS

In order to construct the doubly curved reciprocal frame prototype, we designed and developed a robotic fabrication system capable of gripping, cut-

ting compound angles, and positioning cut timber elements in the placement position. The quadrilateral reciprocal frame required a specific set of robotic routines to be defined for the fabrication procedure, this was achieved by developing integrated systems between multiple toolings through the main program logic controller to the Kuka controller via ethercat. The fabrication procedure calls upon this tooling for the robotic routine the material pickup, cutting and assembly of the reciprocal lattice wall.

### *Design of Robotic Cell Setup*

The robotic cell was designed as a multifunctional robotic system for timber construction. The system was designed and implemented to process a variety of processed and unprocessed linear timber along with wood panels in various dimensions. The Kuka robotic arm was equipped with an automatic robotic tool changer, allowing a variety of tools to be controlled from the integrated system PLC for wood fabrication.

*Robotic Cell Components*, one industrial Kuka robotic arm mounted a linear axis 5m in length. The robotic cell featured two build platforms (one at 3m by 2m and the other at 1.5m by 2m), a Schunk pneumatic parallel gripper for material holding during the robotic routine, and a linear actuated saw station. The setup is depicted in (Figure 7) The entire cell was integrated into a safety PLC for operator control and safety. Robotic routines were stored in the system module (e.g. Saw activation/linear saw control/gripper control), these functions can be called directly from the generated robot code.

*Robotic Cell Security*, working within the robotic cell to allow for fast continuous construction, a specific set of security protocols were in place to minimize operating risk. The operator was protected at all times when the robot was running a routine behind a polycarbonate shield. The robotic controller was limited to a manual mode speed of 250mm/s, as the path planning was simulated in the KUKA|prc through a number of repetitive steps with variable positions for cutting and placement within the robotic fabrication loop. Due to these variable positions, the robot was limited to manual mode to mitigate robotic code simulation discrepancies.

### *Robotic Tooling Development*

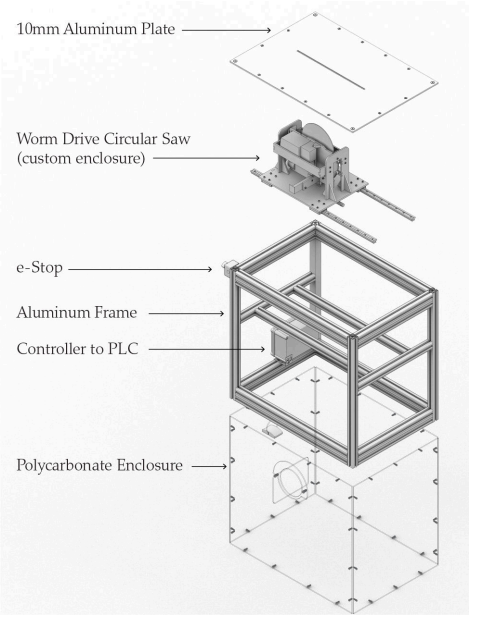



Figure 6
An exploded view of the saw assembly.

The generated geometric model allowed for constraint based analysis of the fabrication tooling. Development of gripping, cutting and placement was analyzed within the reciprocal frame computational model to re-inform the computational model for limiting factors, while generating specific requirements for the integrated robotic tooling. In order to precisely cut the compound angles within the reciprocal lattice structure, we developed a linear actuated saw integrated with the control PLC for calling from function within robot code. The saw (Figure 6) was constructed from a series of components (1) a worm drive saw with a 130mm blade mounted in a custom frame assembly, (2) a linear actuator with a speed of 41 mm/second, (3) control box for PLC integra-

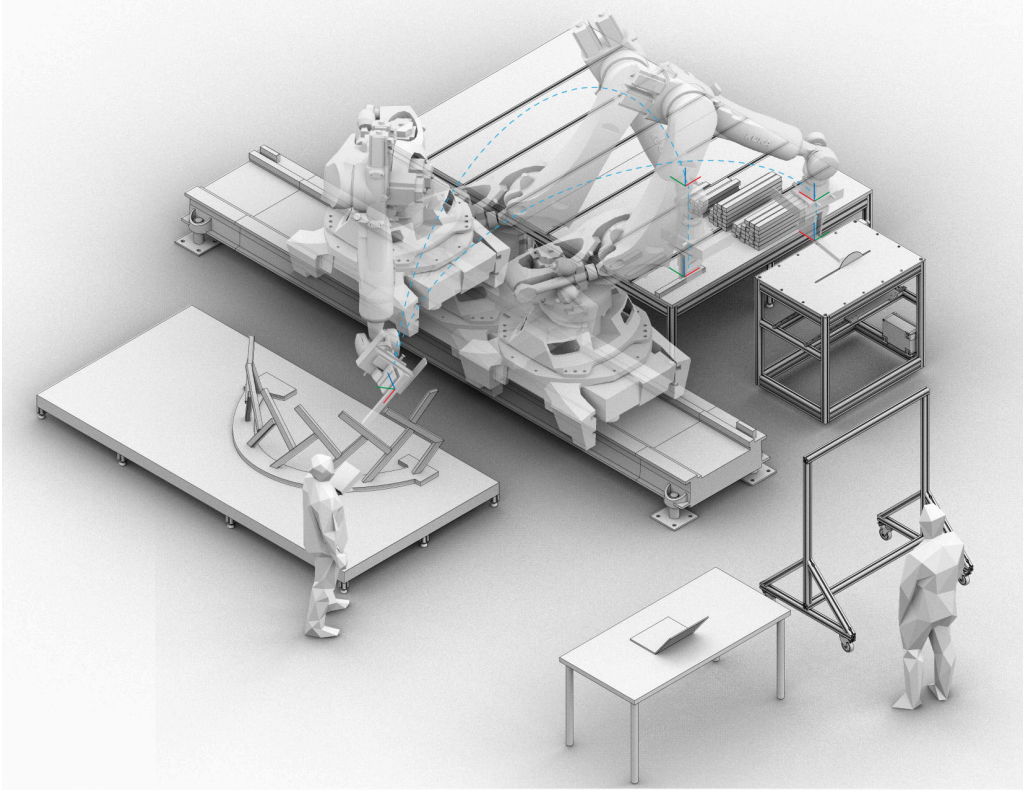


Figure 7
Robotic Fabrication Cell: 1 platform for reciprocal frame construction, 1 sorting and pickup platform, linear actuated sawing station, KR150 R2700 with 5m linear axis, Schunk pneumatic parallel gripper, safety shield for robotic operator.

tion and saw control, (4) structural frame with polycarbonate enclosure. The saw traveled along linear rails via the actuator, allowing a cutting distance of 200mm with 76mm cutting height. The linear actuated saw was integrated through the security PLC and control PLC to allow for saw activation and linear activation from KRL robotic code. The functions defined within the Kuka controller module allowed for the linear travel time domain to be updated the length of cut in the cross sectional area of the beam.

### *Fabrication and Assembly Procedure*

The fabrication loop comprised a series of primary steps which were augmented with subroutines dependent upon the beam analysis. The primary robotic fabrication loop consisted of material pickup (Figure 8a), material cutting (Figure 8b) and then positioning to final placement for fixing (Figure 8c). Within material pickup a sorting algorithm was run to generate a series of rough pre-cut lengths, these lengths were assigned to pick up locations on the material platform, allowing the robotic code to pick up the rough cut length based on the cut beam length. The beam was cut at both ends by orienting the compound cutting plane to the saw blade plane. Due to saw limitations, rough cut material was trimmed to desired length prior to the compound cut procedure. Therefore, each beam was cut twice at each

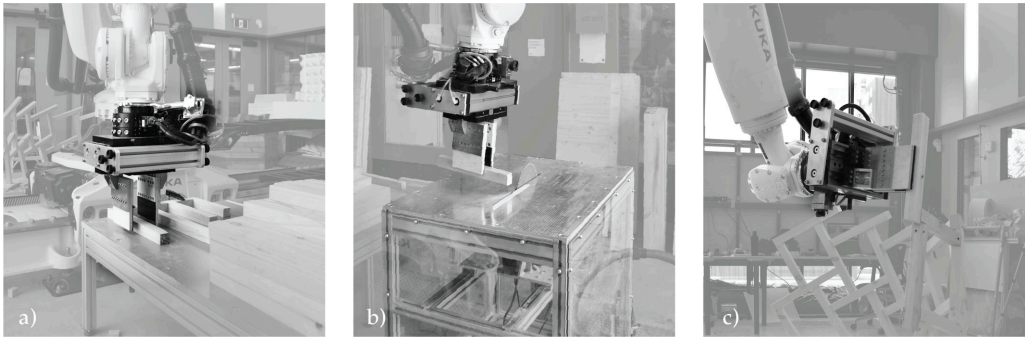



Figure 8
a) Robotic pick-up station, with four predefined rough beam lengths; b) Robotic cutting with linear actuated saw station; c) Placement of timber element for mechanical fastener securing.

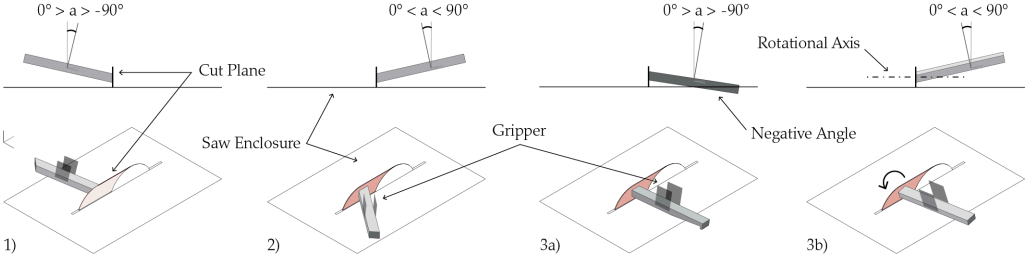



Figure 9
Cutting positions at the saw; the sequence of solutions was filtered until no collision was found.

end. Within our research all cutting angles could be resolved by filtering the beam planes through a set of subroutines for saw positioning (Figure 9):

1. All beam cut planes were first oriented to the left cut plane of the blade.
2. If the angle between the table saw surface and the subject beam was negative, meaning the beam would collide with the saw, the right cut plane of the blade would be used.
3. If the use of the right cut plane still resulted in a negative angle, the beam would be called out and rotated manually around the normal of the cut plane until the angle was no longer negative.

The final step for the robot arm was to position the cut beam for fixing. In order to avoid collisions and guarantee adequate amount of maneuverable space for the positioning, we concluded that the approaching vector to the final placement should be derived from the beam's end plane that would come in contact with the assembled elements. The technique was to allow the beam to reach the assembled beam at a diagonal angle, and adjust discrepancy in the assembled structure along its way.

While the beam was being held in place, it was manually attached to the two installed beams with wood screws. Holes were calculated and manually pre-drilled to avoid splitting the wood. The screw went in along the grains of the beam into the other which had wood grains crossing the screw's direction (Figure 3), allowing the screw threads to bite into the wood grain.

## CONCLUSION AND DISCUSSION

The goal of our research was to encapsulate a computational design model which could re-inform the fab-

rication system through joint, timber and geometries limitations. The developed computational model allowed for the input of doubly curved surfaces to UV mapping subdivision. This has proven to be a robust analysis tool for evaluation of the capabilities of discrete linear timber elements to propagate the input surface parameters. The immediate feedback of the eccentricity analysis allowed the manipulation of the design surface to meet limiting factors of geometry due to higher degrees of curvature. Through the eccentricity genetic algorithm, adjustments were made to minimize the global level of eccentricity within the generated reciprocal lattice structure. The computational design tool performed the fabrication analysis of the timber elements to meet the minimum tolerance within the developed robotic system. The developed robotic fabrication tooling and system has proven to be highly capable in the ability to construct the doubly curved reciprocal lattice structure. Through the successful design and construction of the reciprocal lattice wall, these computational tools coupled with a timber robotic fabrication cell have demonstrated doubly curved reciprocal lattice structures are within the scope of production.

The future development of this research is to scale up the fabrication prototype beyond the reciprocal frame lattice wall. Self-supporting reciprocal frames, doubly curved envelopes and canopies are to be explored in the future. Larger geometries can be parsed into manageable components to be prefabricated for assembly on site. This component system had proven stable in the development of the prototype wall, as two modules were fabricated and later assembled as one due to robotic envelope constraints. The reciprocal structural system developed has demonstrated to be robust without full physical structural testing. Mechanical fasteners were placed by hand with only pre-drilling as a means to choose placement. The pre-calculation of mechanical fastener fixing angles and points would allow for the further optimization of the structural capacity of the reciprocal lattice node. Future research would expand the structural computational model while also providing fabrication data for the precise location and angle. The robotic fabrication system can be developed from the analysis of the optimal mechanical fastener angles from the computational structural model. Allowing for further development of the fabrication system to allow for greater precision and expediting the construction.

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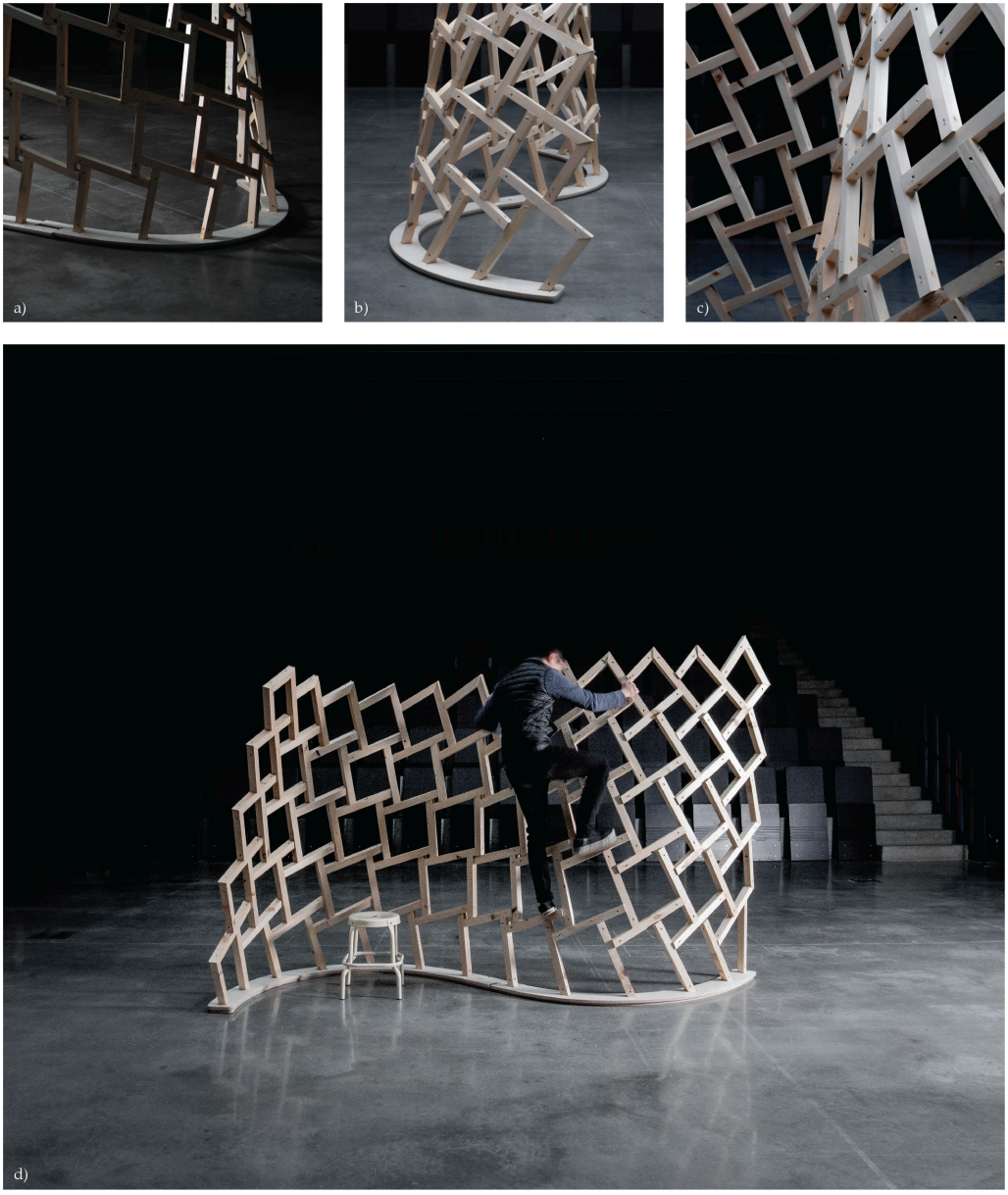


Figure 10
Module A of reciprocal wall B) Module B of reciprocal wall C) assembly of Module A and B D) overall assembly of reciprocal frame lattice wall.

# Design Computation to Robotic Production Methods for Reciprocal Tessellation of Free-from Timber Structures

## *Design, production, and assembly of 100 years Bauhaus wood Pavilion*

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*In a reciprocal frame structure, at any given joint, there are only two members connecting to each other. Therefore, the joints in a standard reciprocal structure are topologically identical. Due to these topological similarities between the joints, the parametric modeling of a reciprocal frame structure applied to a geometrically regular surface, such as domes and symmetric shells, is practical, and it has been explored in several projects previously. In this context, this paper presents an integrated computational design to robotic production process of a free form wooden pavilion with a non-uniform tessellation pattern with differentiated cell sizes. The case study, on the one hand, elaborates on the challenges of solving reciprocal tessellation on complex geometries, and on the other hand, discusses the chosen and developed robotic production approach as a feedback loop that informs the design process.*

**Keywords:** *Reciprocal Structure, Wood Assembly, Design to Robotic Production, Reciprocal Tessellation, Free Form Timber Structure*

## INTRODUCTION AND BACKGROUND

Advancement in digital design and production technologies allows for efficient and effective use of wood as a potentially carbon-neutral material. Beyond automation of building processes in wood manufacturing, the programmability and customizability of robotic fabrication methods provide opportunities for design and assembly of complex structures. In this context, the design-to-production of reciprocal frame structures is studied. The reciprocal frame structure can be defined as structures consisting of linear flat or inclined elements, which support each other and are arranged in a way to form a closed circuit or unit (Larsen, 2014). In particular, in wooden reciprocal structures, the joint design between intersecting elements is challenging in free-form geometries.

While inspiring references of complex wooden joint design can be found in traditional Japanese architecture or Scandinavian woodworks, usually with repetitive geometries, the methods of manual craft and carpentry are not directly applicable and scalable for automated construction. Moreover, architectural scale examples of wooden structures that implement reciprocal systems are few yet enough to be described in three categories in relation to this research presented in this paper. The first category is *regular wooden reciprocal structures*, such as symmetric domes by Shu and Kengo Kuma (Mellado et al., 2014) or even older examples of Da Vinci's self-supporting bridge concepts (Bowie,1960). The second category can be mentioned as *reciprocal tessellation of irregular geometries* like Mount Rokko-Shidare Observatory, designed by architect Hiroshi Sambuichi and Ove Arup and Partners (Goto, 2011). The third type can be categorized as *wooden architectural elements* or even waffle-like structures with cross-halved joints. Examples of this type can be seen in exterior elements of Bamboo Basket shop in Tokyo or Starbucks cafe in Fukuoka-shi by Kengo Kuma, where connections between elements may not be fully considered as a typical reciprocal structure, but yet there are visual resemblances as well as similarities in the method of assembly.

Contemporary applications of digital design and fabrication technologies in wood manufacturing provide examples of moving from repetitive elements and connections to more differentiated components with complex joinery systems (Willmann et al., 2016; Menges et al., 2017). One of the early uses of robotic pick-and-place assembly is *The Sequential Wall* where timbers are laid down on top of each other, with no physical intersection between the elements which have varying length sizes (Gramazio et al. 2010). In *Robotically assembled joints for topology optimized structures*, the produced prototype provides a more complex connection between the ending points of the timbers. In this multi-directional spatial structure, more than two elements are meeting in one single point, which results in three-dimensional cuts at the end of the wooden profiles (Søndergaard et al., 2016). Lastly, in *Timber Shell-Nexorade Hybrid*, by combining timber elements and plywood panels, a hybrid system is introduced in such a way that avoids complex connection detail design and production (Mesnil et al., 2018).

The research objective of the presented case study is to rethink the design and production of free-form reciprocal wooden structures by developing and implementing integrated computational design to robotic production processes. In terms of connection design, one the one hand, the goal is to benefit from the potentialities of robotic production and, on the other hand, consider two elements per joint as the constraint or guiding principle of reciprocal systems. Among various possibilities of tooling such as nailing, screwing, gluing, milling, and spatially connecting (Eversmann, 2019), multi-directional robotic milling is explored in order to achieve the required complexity in material removal from the reciprocal elements. This paper introduces and discusses the tessellation methods of free-form surfaces with varying sizes of cells and elements as the key research problem and design challenge.

## CASE STUDY: 100 YEARS BAUHAUS WOOD PAVILION

As a part of the *100 Years Bauhaus anniversary* event in the City of Dessau, and by studying the historical impact of *the Bauhaus Arts and Craft movement* in architecture, the case study of this research is a wooden pavilion structure. The pavilion is designed based on a reciprocal frame structural system using digital design and production technologies. The following section elaborates on the developed computational design, robotic production, and assembly methodologies. The descriptions are provided in three sub-topics: Reciprocal Tessellation of Free Form Structures, Architectural and Structural Form-Finding, and Robotic Fabrication. The two first topics are explored and developed in parallel, while the third domain provides feedback for materialization, which means that the research behind solving the

tessellation in the micro-to-meso-scale is as important as macro-scale design, such as structural and architectural form-finding procedures. Therefore, the tessellation method is explained first as the primary research challenge, and the other two sections are written in such a way that they can be read independently.

### *Solving the Tessellation of free from reciprocal structures*

In order to solve the reciprocal tessellation of free-form surfaces, the research is conducted on two scales. The first scale is the micro-to-meso, which is concerned with each reciprocal frame in relation to the neighboring cells. The second part is the macro-scale, for which two strategies are developed to populate reciprocal frames on any given free-form surface.

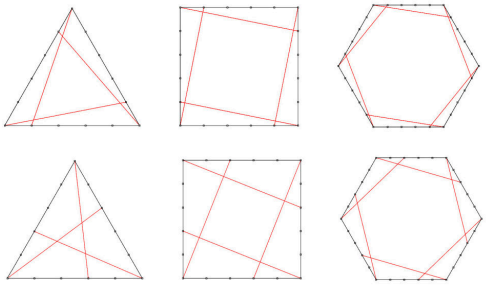

Figure 1
Parametrization of reciprocal frames with different topologies, reconstructed lines based on shifted indices as points on the divided edges

Different topologies such as triangle, square and hexagon are studied as 2D planar cells. Reciprocal frames have overlapping members in such a way that each intersection receives only two elements. To parametrically model reciprocal frames, firstly, edges are divided equally with n-numbers of points, which result in a list of indices associated with each edge of the cell. Secondly, to construct the reciprocal elements as lines between two points, shifting patterns in the indices are studied. By connecting each initial index [0] to the shifted index [i] of the adjacent edge, a line is constructed as the reciprocal element. The higher the shift step, the deeper the intersection and smaller surface area in the middle (Figure 1).

The next step is the 3D rotation of each element using the midpoints of the shifted edges as the center of rotation. On each planar reciprocal cell, the axis of the rotation is the perpendicular vector to each element. The angle of the 3D rotation is decided based on the type and the thickness of profiles in such a way that overlaps in case of tubular metal profiles, or sufficient physical intersection in case of wooden timbers, between elements is achieved. As an example, with the 30mm x 60mm timber profile and cell size of 600mm in diameter, angles between 6 to 13 degrees are acceptable (Figure 2).

To further set the sizes and proportions of reciprocal units, two prototypes are robotically fabricated. In the first try, the notches are applied to only one of the intersecting elements, which results in less tooling time with the robot. In the second prototype, the intersecting elements share the total required depth of the penetration equally. While both methods result in stiff reciprocal units, the second approach is chosen. This decision is considering the physical assembly of the elements with minimal difficulties as well as the fact that in the second approach, the probability of fracture is lower as the material removal is less per element. Moreover, by extending both ends of each profile, the required strength of the elements is achieved. The extension is important, especially where the connections are close to the endpoints of the profiles. This initial fabrication feedback provides the required information for materialization in the following phases of the design process (Figure 3). More information is provided in the third sub-topic of the case study.

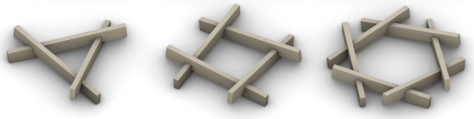

Figure 2
3D rotations around the normal planar axis that results in acceptable intersections between reciprocal cell elements

In the next phase of solving the tessellation, two approaches are tested on the macro-scale. While the first method is mainly based on *curvature analysis* of free-form surfaces, the second method *recursively*

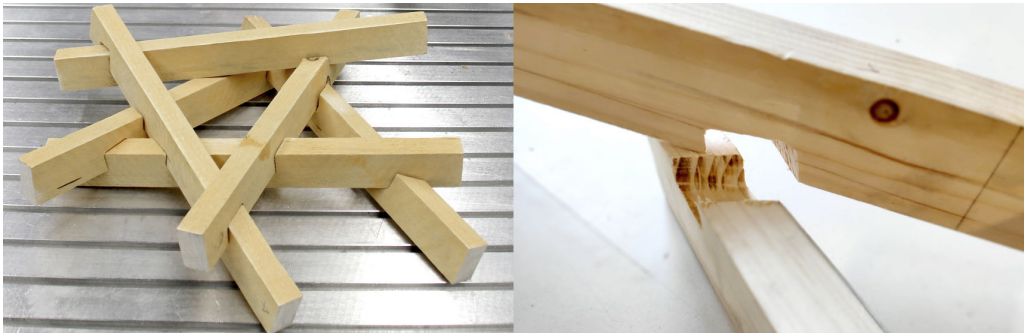

Figure 3
Left: Robotically fabricated prototype of the first two reciprocal cells, Right: a reciprocal connection in which the notches are introduced on both members

*grows* the reciprocal cells on the surface, taking multiple design considerations and assembly constraints into account.

The method based on curvature analysis takes a free-form surface as an input. While the subdivided surface that holds cells is a triangulated mesh, the input to be used for curvature analysis is required to be a NURBS. First step is the 2D shifting routine which is applied to the three edges of each triangle as it is previously explained in figure 1. Secondly, the mid-points of each shifted edge is projected to the NURBS surface, and the curvature values of the surface associated with the projected points are retrieved. The mid-points are projected to the surface considering the closest distance. Then, these values are used for 3D rotation of the elements in order to construct the reciprocal members with physical intersections (Figure 4).

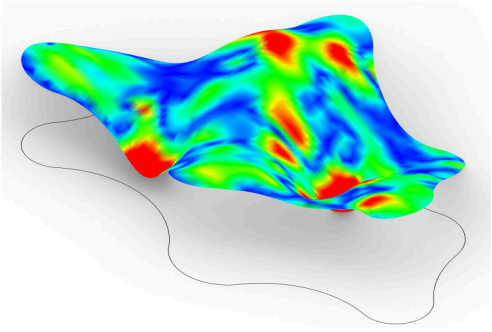

Figure 4
Values extracted from curvature analysis of free form pavilion surface to be used for solving the reciprocal tessellation

On a free form surface, elements in the areas with higher curvature require less rotation, while elements in the areas that have lower curvature take more rotation to obtain the necessary physical intersection between reciprocal neighbor elements. Therefore, the absolute mean curvature values, which are different for each edge, are remapped to the target range of rotation angles in such a way that all timber elements intersect appropriately. While this method is promising and applicable on a variety of freeform geometries, yet in some cases, such as surfaces with kinks or complex anticlastic surfaces, the desirable intersection might not be achieved between all elements.

In the second method, instead of starting with the edges, the process begins with the vertices of triangulated mesh with varying face sizes that approximate the free-form NURBS surface. Then, on each of the vertices, circles are generated with radii corresponding to the surface area of each mesh face. The orientation of each circle is aligned with the tangent plane of the NURBS surface at the evaluated point. The evaluated points are the same as the circle centers and the same as the vertices of the mesh faces. Here, the axial lines of reciprocal elements are generated based on these circles in such a way that all lines are tangent to a pair of corresponding neighbor circles. In the next step, the generated lines are used as the Z vector of the Cartesian planes that set the orientation of the rectangular wooden profiles. In this

case, the XY values of the generated Cartesian planes, which control the orientation of the profile around the axial lines, may not necessarily result in proper connections between the intersecting wooden elements, since the axal lines are three-dimensionally oriented. (Figure 5).

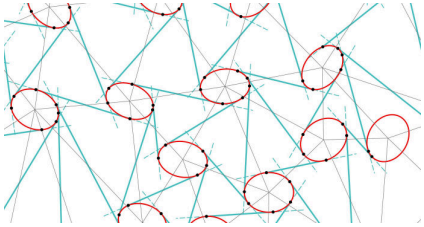

Figure 5
The second method based on circles on the vertices of the triangulated mesh

In order to adjust the orientation of the profiles, a recursive evaluation routine is developed. Meaning that the evaluation process may start from one joint in the structure, check and adjust the connection, rotate the profile as needed and move to the next neighbor element, and recursively repeat the same evaluation routine until all connections meet the criteria. The fitness criteria consider the fabrication method as well as having equal shared notches between the intersecting elements. This strategy suggests that each slit ends up with three faces, as it is proven to be practical in the second prototype shown in figure 3. In this process, the criterion of having three faces per connection is checked geometrically, while in order to force the profile closer to each other at the intersections, the Kangaroo Physics solver in Grasshopper Plugins of Rhinoceros® is used. In the final surface of the designed pavilion, the recursive loop starts simultaneously from the three anchor points, adjusts the connection and moves toward the upper peripheral edges of the free-form pavilion surface (Figure 6).

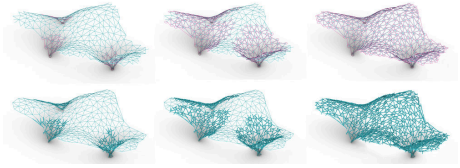

Figure 6
Recursive method of solving tessellation for the free-form reciprocal pavilion

## *Multi-Scalar Form finding and Materialization*

On the macro scale, the parametrization of the design-space simultaneously takes multiple architectural and structural factors into consideration. Meaning that while the overall configuration of the pavilion canopy is informed based on contextual parameters such as physical obstacles as well as human movements and interactions, the structural form-finding routine is implemented in parallel. The outer free-form peripheral curve of the pavilion is bounded inside a 6.5m x 10m plot. In order to define the main pathways towards the plot and position the internal activities, the outer peripheral curve is parametrically adjusted according to on-site observations as well as isovist analysis that considers surrounding buildings and obstacles (Figure 7).

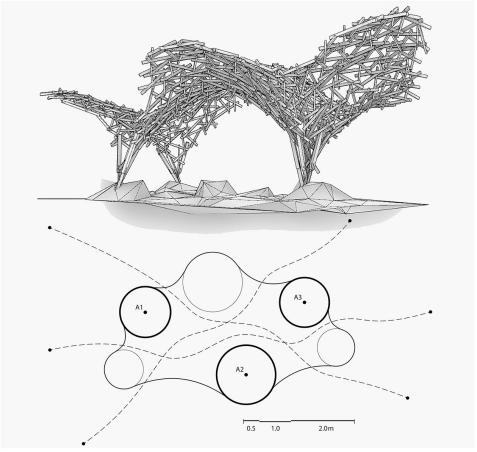


Figure 7
Parametrization of the peripheral freeform curve of the pavilion and the overall architectural configuration

The next phase of parameterization is transforming the 2D projected surface of the pavilion boundary into a free-form 3D mesh surface with the right resolution. Moreover, three anchor points are introduced as supports within the projected boundary area that holds the structure. These anchor points can freely move on the 2D surface inside the pavilion boundary, avoiding the obstacles and considering the activities under the canopy. A dynamic mesh relax-

ation method based on counter gravity force is implemented where the anchor points are fixed in Z and free in the XY plane, the points on the peripheral curve are fixed in XY and free only in Z, and all the other vertices of the mesh are free to move in all XYZ directions. The reason behind moving the vertices on the peripheral curve only in the Z direction is to avoid drastic deformation and to maintain the boundary shape of the pavilion during the 2D to the 3D relaxation process.

Additionally, the initial resolution of the triangulation of the 2D surface influences the mesh relaxation process. The final resolution is set with 300 populated points on the 2D surface, considering two main sets of factors. Firstly, parameters such as the feasible size range of reciprocal units, total quantities of elements, and fabrication effort are taken into account. Moreover, the resolution influences the dynamic mesh relaxation process in terms of the required computational processing power as well as the quality and topology of the resulting mesh, especially on the peripheral edges of the relaxed mesh.

With these three parametric systems being set, which are: 1) adjustable anchor points, 2) changeable mesh resolution, and 3) dynamic relaxation of the topology, the parameters of the design-space are defined. Moreover, a structural analysis routine is linked to the parametric model in order to evaluate the structural stiffness of every possible outcome generation in the design-space. The preliminary cross-section material for all the elements is set to be a type of wood that can hold Fy=1.3kN/cm2. Further, a set of predefined wooden profiles are considered as the input timber profile options. In this project, considering the material supply and fabrication effort, the number of options is reduced to two, which are 50mm x 120mm and 50mm x 70mm. This results in a variation of cross-section profile through the pavilion, as it is shown in one of the design generations in figure 8.

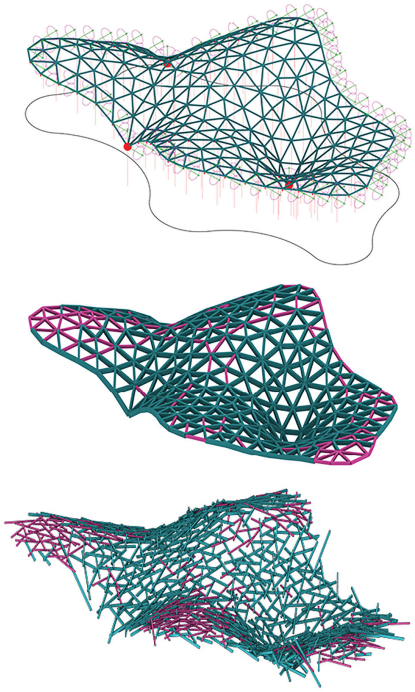

Figure 8
Top: Parametrization of the design-space defined with the adjustable anchor points, changeable mesh resolution, and free-form mesh to be dynamically relaxed; Middle: Materialization of the cross-section with varied profile sizes; Bottom, Applying the second method of reciprocal tessellation

The following step is to explore the design-space using a Multi-Objective Optimization (MOO) solver to find the optimal configurations. The objectives are: the mass to be minimized, the total accessible average height to be maximized, the total structural displacement on all vertices to be minimized, and the total internal elastic energy to be minimized. The add-on plugins used in Rhinoceros-Grasshopper3D are Wallacei as the MOO solver and Karamba3D for structural analysis and profile assignment. Eventually, among the multiple optimal generations, the most fitting one is chosen for further fabrication and design development (Figure 9).

### *Robotic Production and Assembly*

Parallel to the computational design workflow, several prototypes of reciprocal structures are produced and different methods are tested. In order to estab-

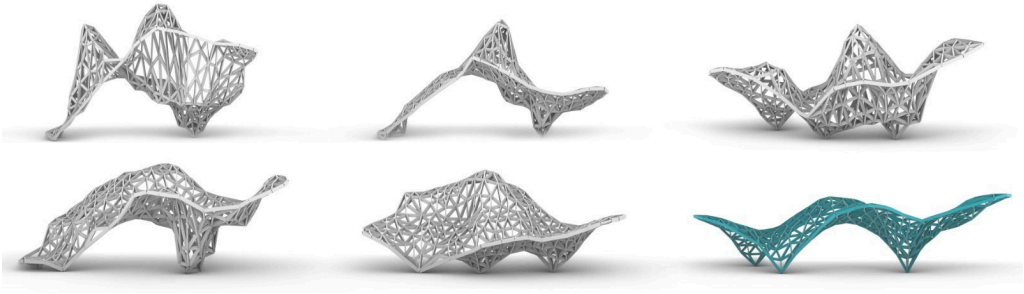

Figure 9
Multi-Objective Optimization exploring the design space to find the optimum solutions

lish a generic system that considers the variations in the dimensions of the profiles, the numbers of the connections per element, and the angles and depths of the cuts, a parametric design-to-robotic production method is developed. Incorporating the inverse kinematics simulation of the robotic production process suggests two types of material removal approaches. In both methods, a milling spindle with a flat-nose is used. The first approach is the *Layer-by-Layer removal* method, where the orientation plane of Tool Central Point (TCP) at the tip of the milling bit is aligned with the orientation plane of the bottom surface of the cut. The second tooling routine is *perimeter removal*, which directly cuts the perimeter of the slit, without crushing the whole material inside the joint, by aligning the direction of the milling bit to the three surfaces of the cut. While the second method is faster, for some ranges of out-of-reach angles, the first method is required. However, using the second method results in round edges between the surfaces of the cut, which may prevent the two elements interlocking perfectly together. The radius of the fillet depends on the diameter of the milling bit. Therefore an offset towards outside of the cut for all three surfaces is required to control the fabrication tolerances (Figure 10).

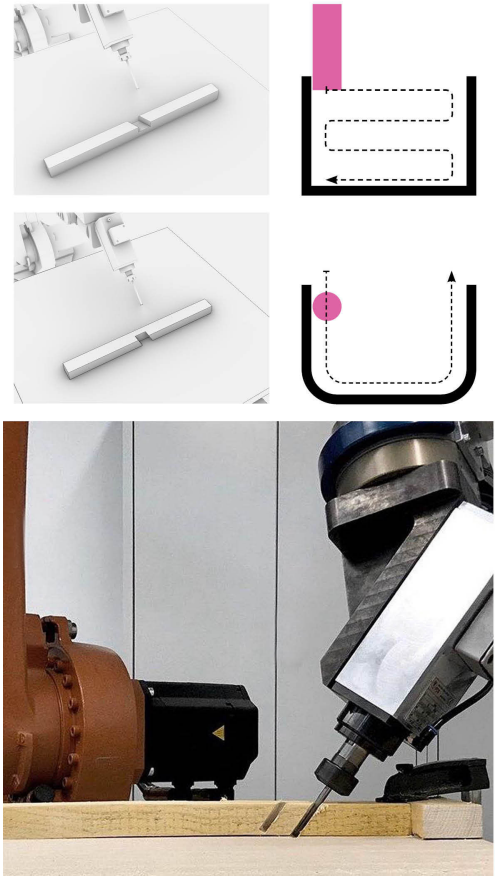

Figure 10
Two methods of toolpath generation for material removal: Layer by Layer removal on the top and perimeter removal without crushing the material in the middle and bottom

By using the developed robotic toolpath generator, three initial tests are produced before the final pavilion prototype. In the first case, the focus is on one reciprocal unit where a 30mm x 60mm wooden profile is used, and cuts are only introduced on one of the intersecting members. The second case uses the same type of detail for intersections, where multiple units are produced and assembled together to form a larger mockup with hexagonal reciprocal cells. Instead of wooden profiles, 50mm x 70mm Expanded Polystyrene (EPS) elements are used for faster production and testing the proportions of the final designed pavilion. While the production effort is considerably less with this type of intersection, the assembly process is challenging as there are no reference contact points on the corresponding reciprocal elements. Therefore, the halved joint detail is tested in the third case as well as the final pavilion prototype to overcome the assembly challenges and reduce the risk of fracture of the elements.

The final presented prototype in this paper consists of 78 reciprocal wooden elements with varying sizes in length ranging from 500mm to 1700mm that together form 26 reciprocal cells. The prototype is a segment of the designed pavilion, and it is taken out from the areas around one of the anchor points to produce a reciprocal structure that has high surface curvature. The profile cross-section is set to 26mm x 50mm by considering the available material resources, the applicable payload of the KUKA KR-16 robotic arm, as well as the estimated time for the production and assembly. In order to double-check the structural stability of the prototype, the model is analyzed by implementing the same structural analysis routine developed for the form-finding and materialization. The total time of producing all the joints with an 8mm flat-nose milling bit is roughly 12 hours, which includes supervision and the positioning of pre-cut elements in front of the robotic arm. Most of the elements are receiving two cuts. However, in some cases, there are three or four notches where the extended ends of reciprocal elements collide with more than two nearby elements. Cuts are mainly produced using the perimeter removal method, and few cases are produced using the layer-by-layer approach. To hold the structure during the assembly zip ties are used to stiffen the connections (Figure 11). The ties will be removed after all reciprocal cells are self-supporting each other throughout the complete shell surface.

## CONCLUSION AND DISCUSSION

This project presents the development of a computational design to robotic production workflow for reciprocal wooden frame structures. Computationally solving the tessellation of free-form surfaces, while considering all the required geometric constraints and fabrication potentialities, appears to be a key factor in this research. The proposed methods for tessellation provide solutions for a variety of complex geometries. Further improvements can be made for freeform surfaces with multiple opposing curvature directions like anticlastic surfaces. An instant solution for extreme curvatures is to increase the tessellation resolution, which then results in larger quantities of elements hence more fabrication effort. Therefore, in this project, the size variation of reciprocal cells is explored and tested. Defining the cell sizes based on the surface curvature, on the one hand, may result in interesting architectural qualities and, on the other hand, may structurally explain the differentiation of profile cross-section. Theoretically, it is possible to vary the profile section of every single reciprocal element to optimize the structural performance further. However, practically a balance between the availability of material resources, quantitative performance measurements, qualitative design objectives, and fabrication strategy is required. In this context, one of the future directions for this research might be the integration of robotic pre-cutting of elements with varied shapes and dimensions.

Reciprocal systems are a type of self-supporting structure which are introducing a range of opportunities to develop alternative assembly strategies of freeform wooden structures. While providing the freedom to produce complex joint design using

Figure 11
Top: The final prototype with 78 reciprocal elements varying in size ranging from 500mm to 1700; Bottom: Close up of the connections after the ties are removed

robotic tooling can influence the assembly logic, further explorations can be conducted to automate the process of connecting the elements together. This may suggest the development of robotic assembly setups with multiple manipulators or human-robot collaboration where augmented reality could assist the assembly processes and inform the design accordingly. Learning from the manual assembly process of the final prototype, it is worthy of mentioning that the basket-like shape of the prototype provides stability while connecting the units together. Moreover, as the tagging sequence follows the very same order of recursively generating the reciprocal members starting from the anchor points, the structure remains stable during the assembly process.

## ACKNOWLEDGMENTS

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# Design Process for a Soft Flexible Palm

## *Improving grasp strength in an anthropomorphic end effector for collaborative robots in construction*

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*This paper describes an iterative design process to create an anthropomorphic end-effector for a collaborative robot in construction. The focus is on improving the palm or juncture of the handlike end effector. Anthropomorphic end effectors typically have stiff, rigid palms that only provide support to the fingers rather than being an active part of the end effector. This research contributes to new knowledge through a detailed investigation of the role the palm has in improving the grip strength and control. This control and strength is essential for operating tools commonly used on construction sites. Consequently, the paper asks the question and investigates if a flexible palm could provide added support and grip for end effectors needed for complex processes.Via an action-based research method, the paper uses soft robotic techniques to experiment with a range of pneumatic iterative solutions to create a functioning palm, inspired by the human hand. The resulting end effector will aim to mimic the behaviours of the human hand.This investigation, its proposed hypothesis, methodology, implications, significance and evaluation are presented in the paper.*

**Keywords:** *End Effector, Hybrid Tools, Soft Robotics, Anthropomorphic*

## INTRODUCTION & BACKGROUND

### *Collaborative robotics, end effectors & Construction*

Collaborative robots are purpose-built robots or robotic arms that work alongside or near humans. With Industry 4.0 initiatives looking at technical assistance to aid human workers to reach their full potential, collaborative robotics are becoming an alternative solution for manufacturing companies (Østergaard, 2016). Collaborative robots could also help change the construction industry by solving some of the current problems at hand. Adversity such as labour shortage and production downfalls could be solved by collaborative robots completing work that could be deemed unsafe or affecting one's health onsite as argued by Reinhardt et al. (2019). However, collaborative robots would need to meet a range of requirements to work safely in unstructured environments like construction sites [5]. This focus can be seen through prior research, by Reinhardt et al. (2019) that looks at the tasks that a robot could collaborate on such as the construction of a stud wall

and the use of tools. Whereas, other literature points out the advantages of collaborative robotics in construction (Afsari et al., 2018) it fails to focus on the relationship of tools used on construction sites and the role end-effectors play. Consequently, this research investigates the design and application of anthropomorphic end effectors for collaborative robots. These are an important part of the solution to moving collaborative robotics onto construction sites.

### *End effectors*

By definition, end-effectors or end of arm tooling are the devices that attach to the end of a robot arm, intended to interact with the environment. End effectors are crucial elements to ensure the functionality and efficiency of a robotic application. With robots and in particular collaborative robots, moving into complex environments like construction, with high levels of human-machine interaction, it is imperative that end effectors are re-designed from simple grippers to multifunctional, intelligent and safe tools. The market for collaborative end effectors is increasing, between 2017 and 2018 alone; it had a 23% growth rate [3]. However traditional end effectors do not suit a lot of collaborative environments because they are usually designed with hard metals or plastics and rigid links that could cause injury to human coworkers upon collision (Rus, 2015). Further, current end effectors are predominantly two-finger grippers that limit their activities to pick and place functions, thereby restricting the range of objects they can work with. Anthropomorphic end effectors, on the other hand, use similar characteristics to the human hand to increase the range of objects and tools the hand can pick up. Since 2001 there has been an increasing volume of research in the field of robotic hands or anthropomorphic end effectors (Xu, 2016; Walkler, 2004; Butterfaß, 2001; Konnaris, 2016). Although many are successful, there are common themes noticed throughout each design. The design of fingers has been prioritised over the design of the entire hand. Furthermore, most commonly fingers are intricate and can complete dexterous tasks. However, the palm junction is designed for use, purely as a base to fingers and a support tool that adds rigidity to the overall structure (Ibid., Alspach, 2018). The human hand does not work in the same way; the palm plays an integrated role in performing particular grasps, such as a power grasp.

## MOTIVATIONS AND AIMS

The manufacturing industry's fabrication processes have transformed through the use of robotics over the last three decades. This can be seen in Industry 4.0's focus on cyber-physical systems that allow robots to make decentralised decisions for automated processes (Firth, 2019). The Architecture, Engineering and Construction (AEC) sector are increasingly adopting these workflows and fabrication techniques. Evidenced by government funding for research initiatives in Building 4.0 [1] and the Integrative Computational Design and Construction for Architecture Cluster of Excellence [7]. These initiatives investigate the potential for digital and robotic fabrication, both off-site (in a factory), and on-site (construction site). Rosenberg et al. (2015) suggest a shift to collaborative robots (Cobot) from industrial robots could increase the safety and opportunity for on-site robotic fabrication.

The motivation for this research has been informed by the findings described in the paper "Towards a novel methodology for workflow capture and analysis of carpentry tasks for human-robot collaboration" Reinhardt et al. (2019). Reinhardt et al. identified through their research of two construction workers who used a total of 5 tools (Circular Saw; Concrete Nail Gun; Hammer; Measuring Tape; and Nail Gun) over a 30 minute period to construct a stud wall. The research recorded empirical observations of all tools and physical movements.

Consequently using the data recorded, on average, every 6 minutes, a new tool was used. To replace a construction worker with a Cobot to complete tasks or physical movements outlined in Table 1(Ibid.), there could be two resulting trajectories. Option (1) the human will operate all the tools, and the

Table 1
Node Table noting repetitive actions and use of tools over 30 minutes (Reinhardt et.al 2019)

**Nodes Table**

| Physical Movements | Files | References | | Use of Tools | Files | References |
|---|---|---|---|---|---|---|
| Bracing | 1 | 1 | | Circular Saw | 3 | 6 |
| Carrying (1x Carpenter) | 1 | 1 | | Concrete Nail Gun | 3 | 7 |
| Carrying (2x Carpenter) | 3 | 16 | | Hammer | 3 | 11 |
| Changing Nail Gun Cartridge | 1 | 1 | | Measuring Tape | 1 | 1 |
| Cutting | 3 | 5 | | Nail Gun (1x Carpenter) | 2 | 5 |
| Hammering into Position | 3 | 5 | | | | |
| Lifting / Sorting | 2 | 5 | | | | |
| Loosening Straps | 3 | 5 | | | | |
| Measuring | 1 | 1 | | | | |
| Passing Tools | 1 | 1 | | | | |
| Position with Feet | 3 | 15 | | | | |
| Short Vertical Lift | 1 | 1 | | | | |
| Sliding Frame | 2 | 2 | | | | |
| Supporting in Position | 2 | 3 | | | | |
| Vertical Rotation | 3 | 14 | | | | |

Cobot will assist by passing, lifting or sorting tools or (2) both humans and Cobots will use the required tools. Option (2) provides more assistance to human co-workers; this trajectory was chosen. Although, it was observed that this option would require workers to change tools every 6 - 12 minutes. For a Cobot arm, a tool change translates into an end-effector change which is a time-consuming process requiring mechanical and digital calibration each time. This makes option (2) unproductive and time intensive without an anthropomorphic end effector.

As a consequence of the above findings, (Firth, 2020) argued that anthropomorphic end effectors could ensure efficiency on site. This end-effector needs to be able to use the tools on a construction site that are designed for the human hand in order to be productive working with humans(Ibid). Not only is this important, but it could improve safety as human-like motion can be intuitively understood by humans, allowing anticipations of robotic movements. (Konaris 2016). As shown in Reinhardt et al. (2019), intermediate tasks such as lifting, sorting and passing tools between co-workers are required to complete one task. An anthropomorphic end-effector could complete tasks from both option (1) and (2) described earlier, whereas a tool specific end-effect could not.

However, commercially available anthropomorphic end-effectors or robotic hands have their limitations for use within the construction due to the current designs. These end-effectors or robotic hands focus on the dexterity of the fingers, and the palms and hand junction provide only a supportive base. Tools in construction require the functional benefits of a palm which include the arches that provide balance and stability to be able to accurately carry out tasks and support the weight of tools such as a hammer or a screwdriver. Soft end-effectors are also being developed for grasping delicate objects (Mahanta, G,et al. 2019) and are not focusing on replicating strength in soft systems. The aim of this research is to create preliminary designs for a functional palm influenced by research findings in anatomy, robotic engineering and material research that can create strength and stability needed for heavy tools.

## OBJECTIVES AND OUTCOMES

The objectives of the research are listed below:

1. Understanding the anatomy of the human hand
2. Investigating how the human hand anatomy could be replicated by and translated into an anthropomorphic end effector. A particular focus here is on replicating the tissues of the hand and

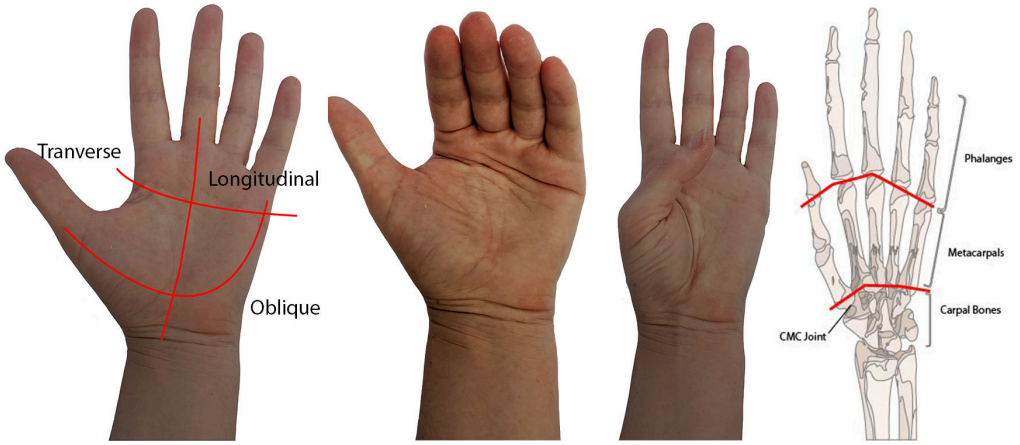


Figure 1
Anatomy of hand

particular arch movements and muscular movements that allow for some of the most crucial movements required to grasp objects. Specifically: (a) Replicating arches (transverse, oblique and longitudinal) in the palm via a 'responsive and actuated' element and (b) Replicating the tissue of the human hand with silicon to address safety concerns of collisions with coworkers.

The research will deliver an outcome in the form of a physical prototype of the palm. Its design will take inspiration from soft robotic techniques such as Pneunets, to have the capabilities to form around an object similar to the human hand when the thumb and fingers are closed (figure 1).

## METHODOLOGY

A design-based approach was adopted to meet the objectives of this research (Tomitsch and Wigley, 2018). The project draws on multiple fields including bioengineering, medicine, material science, industrial and product design to produce a prototype. The first step of this research was to conduct a literature review on the anatomy of the human hand and soft robotic techniques. Here the research investigated certains grasps, such as power, chuck and span, and the functional behaviours on the hand to achieve them. The literature review allowed the researchers to identify the gaps in the field and determine a research trajectory for the iterative design process. The design-based approach used soft robotic techniques to test different types of silicon and chamber patterns in order to improve the movement of the palm of the anthropomorphic end-effector design. Along with understanding movement, iterations were tested to determine how the soft robotic component aided the grasping of construction tools (figure 2).

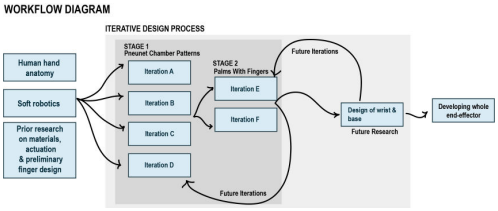


Figure 2
Workflow Diagram

### *Human hand anatomy*

Based on the objectives to design an end-effector that's anthropomorphic, it was crucial to study the

hand's basic motions and anatomy. Literature such as Beredjiklian's 'The Structures of the Hand' [5] or Duncan, Saracevicb, Kakinoki's 'Biomechanics of the Hand' [2] provides an understanding of the required functions of the hand which can be broken down into movements and actuation. This research looked at the movements that aid in picking up heavy tools and use tools on a construction site.

The hand is made up of many integrated parts, including the palm (front side of the hand) and the dorsum (backside of the hand) with 27 bones, all connected to a series of ligament and muscles. These elements, in combination with the fingers, wrist and nervous system, make up one of the most complex organs of the body. It is vital that the palm of an anthropomorphic end effector is flexible, and has similar qualities to the human palm junction. Dominant movements, used for the most common grips, are controlled by the bones, tendons and muscles inside the hand (Watanabe, T 2018). When considering the needs of the construction industry, this research focused on movements such as the power grip, where objects are held in the palm of the hand, and long flexor tendons pull the thumb and fingers to ensure a tight grasp, supported by the palm.

An important element of the hand's operations is the arches in the palm. There are three arches of the hand that run in three different directions, transverse, longitudinal and oblique. These three arches aid this functionality of the palm shaping the hand to balance, stabilise and mobilise. The arches have shown to have significant influence over the muscles that aid the movement of the fingers and thumbs (Sangole 2008). These arches allow for power, chuck and span grasp that are used widely within the construction industry with tools such as hammers and screwdrivers.

The muscles and arch formations, in combination with the bones and joints, are responsible for the dominant movement seen when carrying out specific tasks. The joint between the carpal and metacarpal known as the first CMC joint allows for the opposable thumb, which is then aided through small muscles and the thenar arch (Watanabe 2018) whereas the joints between the metacarpal and phalangeal bone are what allows for the dominant bending motions of the four fingers aided through the longitudinal arch of the fingers (Ibid).

The primary nerves in the arm and hand are the radial, ulnar, and median nerves which all work together to control the muscles of the hand by receiving signals from sensory detectors across the entire hand which detect touch, pressure, temperature and pain. The ability of the sensory system allows the hand to adjust its grip depending on the object and the pressure needed. This system works to control the muscles and joints through embodied intelligence.

Although this research acknowledges the importance of both the bone and joints system and the nervous/sensory systems role in the function of the human hand, this paper focuses on the arches and muscle movements that are required to aid particular grips that are used within the construction industry.

### *Soft robotics techniques - pneunets*

Soft robots are robotic systems that are inspired by nature. Most commonly, soft robots are designed through the study of biological systems that are inclusive of softness and body compliance that helps robots reduce the complexity of the interaction it has with its environment (Rus.D, Tolley.M, 2015). Soft materials such as silicons are successful when interacting with humans as they can absorb impact upon collision, reducing injuries to human co-partners, whereas, their rigid counterparts do not (Ibid). Not only do soft material provide safer environments for human interaction, but soft materials can also reduce the complexity of each component, by reducing rigid joints and links. Earlier research was conducted into the material choice, discussed in "Development of an Anthropomorphic end-effectors for collaborative use on construction sites." (Firth et.al, 2020) which influenced the materials used within this research.

Pneunets, named after "pneumatic networks" designed and developed at Harvard University[4]. are one of the most common types of soft robots.

They have been developed in two parts, the first part is a series of channels and chambers used for inflation which creates a bending motion. The second part is a flat layer, which controls the bending motion by restricting the chambers to expand in a certain direction(Ibid). These two layers are sealed together, using silicon or silicon glue. Pneunets have commonly been used in creating soft robotic fingers for robotic grippers (Deimel, 2016, Zhou, 2017, Zhou, 2019) or robotics that are used for other purposes like walking or crawling (Shepherd, 2011). This type of pneumatic actuator will be tested throughout the design iteration process to test if this is the correct solution to create a flexible palm.

## DESIGN ITERATION PROCESS

The research team experimented with different moulds, that had chamber patterns and palm shapes to create a preliminary design that was capable of replicating the human hand, informed from the literature review.

### *Development of Basic Palm Shape and Silicon Tests*

The first stage of the iterative process was developing a basic palm shape and then testing the rigidity of different types of silicon such as Platsil Gel 0030, Transil and Mold Star 16A (Figure 3). The initial shapes included chamfers enabling folding but no actuation. Mold Star 16A was found to be too rigid as a palm and in fact, restricted the did not aid the movement of fingers or increase grip and strength. Whereas Platsil-Gel 0030 created the opposite effect. The fingers were able to be actuated and close, similar to the human hand. However, there was not enough structural rigidity in the silicon to support the fingers or ability to form around objects aiding grip strength.

These initial iterations led to a second stage that looked at actuating the palm with pneumatics and layering the silicon to increase structural rigidity in the palm shape. These two elements allowed structural support for the fingers but were flexible to move in the required directions.

### *Design of Palm and Actuation*

The second stage focused on actuation; the aim was to recreate the longitudinal and thenar arches and muscle movements involved. A range of different patterns was tested to measure the resulting movement and pressure when actuated (shown in figure 4). The palm initially was divided into four pieces demonstrated in iteration A, two sections for actuation and two for future sensor systems to be embedded. The thumb showed some movement, but the Platsil-Gel layer with the chambers was too thin, and the silicon only expanded in one area, instead of evenly distributing. The thumb's air chamber successfully created a bending motion, so this design was used throughout the iteration process. The chamber was angled slightly to follow the oblique arch. The upper palm did not show enough bending motion, as the air chamber was too small. The second version of this design was tested with Transil(a previously tested silicon). This type of silicon was unfortunately too stiff to create the bending motion required to imitate the human palm, although this restrictive

Figure 3
Initial Iterations testing different silicons and grooves to represent the shape and movement of a palm.

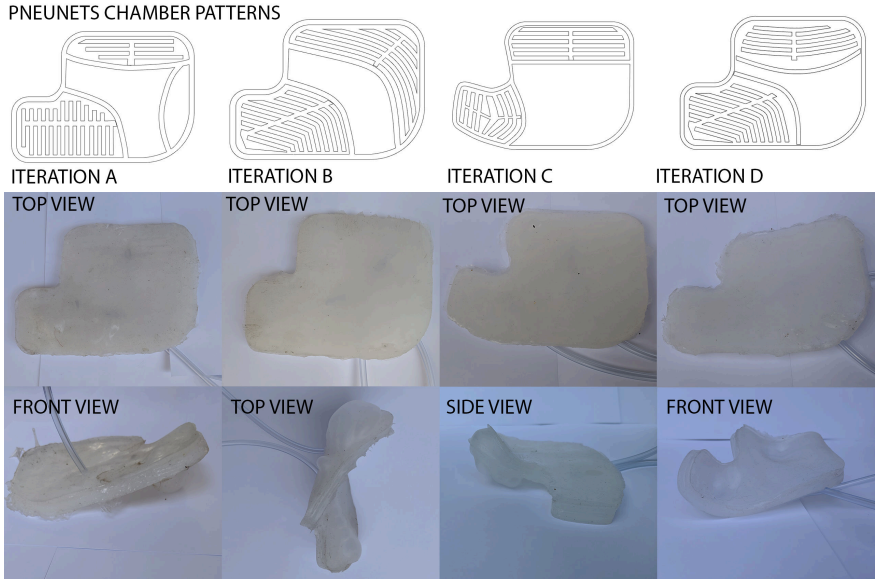


Figure 4
Example of different palm iterations, exploring soft robotic techniques to develop different arches.

quality could be used in the bottom restraining layer to aid controlled movement.

A different pattern was then developed in iteration B, and trialled to test the direction of inflation. The process involved putting the air chambers on an angle to and increasing their size to understand if this assisted in moving the palm. This pattern is shown in iteration B. The increased chamber size dramatically improved movement of the upper palm. Although in this instance, the bottom layer expanded instead of creating strain in the 'thenar arch' section, it expanded, which is not the required effect.

Iteration C focuses on a different shape of the palm, the lower palm and thumb section shape was refined to encourage bending and was angled inwards to change the direction of inflation. Although iteration B's upper palm was most successful; the movement was concentrated in one area, so the palm did not move the desired motion that enabled the fingers to close for a power grip. Iteration C returned to straight chambers but increased size and length for increased inflation.

Other design interventions tested included embedding fabric into the base layer to create further strain and eliminate any expansion of the bottom layer, which hinders movement. Although it successfully stopped expansion in the bottom layer, it also stiffened the silicon thereby reducing the bending motion.

Iterations A, B and C used a base layer that had been moulded to contain pockets that would encase each air chamber. This method was changed in iteration D to have a flat base layer and added chambers that acted as ridges to try to aid the folding process. This was more successful in comparison to the other iterations, shown in figure 4(D). Successful components of each iteration will be used in further experimentations. This is inclusive of;

- Iteration's A, four sections, in the future the two solid sections will be void cavities, to increase motion by reducing weight.
- Iteration's B, chamber size as it allows for higher volume capacity that increased the bending motion.

- Iteration's C, design of an angled thumb that represented the thenar arch.
- Iteration's D, the success of using void cavities to increase the bending motion.

### *Connecting Cable-actuated Fingers*

The third Stage looked at connecting pre-designed fingers that are cable-actuated to the palms developed in stage two. This was intended to test whether there was added benefit to a palm that acted as an integrated component to an end-effector.

The first attempt trialled the fingers being attached to the palm with small rubber tubes that were inserted across the top of the palm. These tubes fed cables down the back of the palm and were reattached to the bottom edge of the palm. This had a negative effect as the cables caused a pulling tension that directly counteracted against the bending motion created by the Pneunets chambers.

The second attempt used a different technique. As seen in Figure 3, rubber tubes were embedded into the silicon as it was setting. This fixes the tube and cables to pull in a singular direction. An unexpected result of this test showed that Platsil-Gel branded 'Smooth-On' would not set when cast next to the rubber tubing. The silicon became a sticky consistency around the tubing allowing it to break through the palm. To resolve this issue experiments the tubing was superglued to the palm for the remainder of the experiments.

As seen in Figure 5, attaching the rubber tubing to the front face was successful for these tests, although a stronger solution needs to be devised before production of the end-effectors for industry use could occur. Figure 5(e) represents the initial test with the fingers attached. The expansion of chambers did not necessarily aid the gripping process in this version. Although the upper palm moved slightly, it was not similar to human fingers bend-

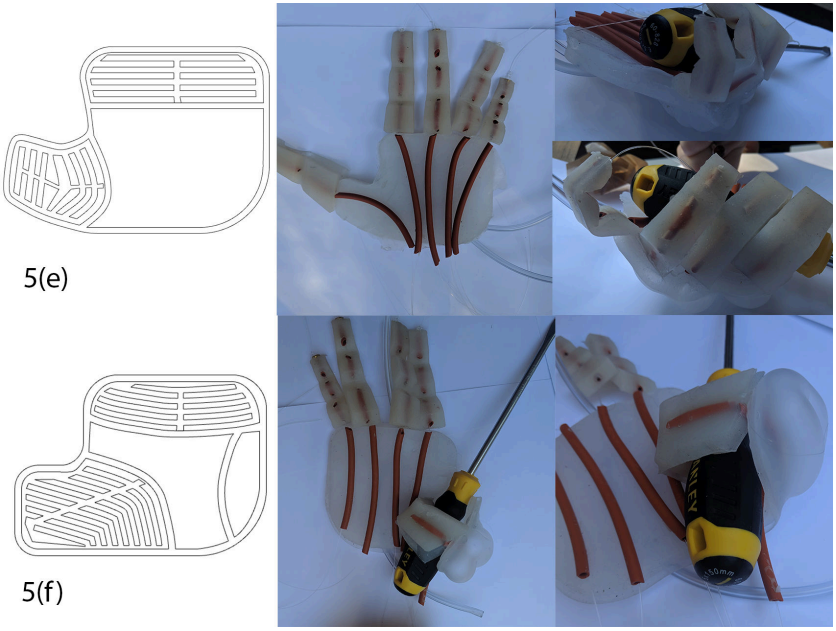


Figure 5
Three Iterations of connecting fingers to the palm and testing the ability to grasp a tool.

ing when influenced by the longitudinal arches and metacarpal and phalangeal bones. The chamber volume and length down the palm would need to be increased, as well as a thinner bottom layer as it was impeding the bending motion.

Figure 5(f) shows the successful iteration of Pneunet chambers that function similar to the thenar arches and opposable thumb. This particular palm was adapted from iteration(A) seen in figure 4. The two layers were changed to include hollow cavities instead of solid silicon layers to reduce weight and improve movement upon actuation. The thumb chamber volume was increased from 25mL to 50mL, aiding a larger range of movement that allowed the cable finger to wrap around the tool and create a stable grip (Demonstrated in figure 5 (f)). Although, in future iterations for both (e) and (f) will need a revised solution for joining the fingers and palm together to ensure neither element range of movement is affected.

## SIGNIFICANCE & EVALUATION

This paper describes an iterative design process that focused on the design and development of an optimised palm for an anthropomorphic end-effector. The purpose of this end-effector is to meet the critical needs of the construction industry for functional, collaborative robotic solutions. The research projects first objective, point (1) were to understand the anatomy of the human hand and how the palm aids grip. Hence, this research focused on key elements and functions of the human hand to replicate elements in point (2) such as longitudinal and thenar arches in the palm that particular aid grasps. This research was successful in its objective point (1) in understanding the necessary functions of the palm that needed to be replicated.

Through exploring pneumatic soft robots for objective's (2) sub-elements (a) and (b), it became clear that it was possible to create a flexible palm that could be integrated into the design of an anthropomorphic hand. Using Pneunets holds both advantages and disadvantages. Advantages included the flexibility of the silicon which allowed for a range of movements that were activated by even small amounts of pressure. The silicon was also flexible enough to allow the palm to move in a determined direction. Disadvantages included the weight of the silicon affecting movement and 'Smooth-On' branded silicon does not set against the required rubber tubing.

From the iterative design process and testing undertaken to date, this research has provided a preliminary study into how the design of the palm affects the grip of construction tools. The research has also successfully demonstrated the incorporation of the arches in the palm into physical models to enhance grip function in an anthropomorphic end effector. This was achieved through the use of pneumatic chambers that form the shape of the human palm once actuated. Not only does this recreate shape but it mimics muscle movements that are required when grasping objects. Future directions of the research will focus on the following key factors:

- Controlled movement of the palm that avoids bending too much in corners, and instead focuses the entire palm structure.
- Increasing the capacity of the volume in the chambers to improve motion and also controlling this volume through programmable systems, like Arduino.
- Developing the base of the end-effector that will house the electronics and attach on the robotic arm but also allow movements similar to a human wrist.
- Focusing on a more "human-like" shaped palm and reducing the amount of silicon used.
- Replacing bones via a 'structural' element and nervous systems with a 'sensory' system.
- Developing a better system of attaching the fingers to the palm without compromising on movement.
- To create cohesive anthropomorphic end effectors that mimic the behaviour of the human hand.

This research is an important step towards an anthropomorphic end-effector capable of using tools found on a construction site, whilst also being collaborative with human coworkers.

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# Voxelcrete

## *Distributed voxelized adaptive formwork*

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*Advances in computational form finding and simulation enable the creation of highly efficient structurally aware freeform geometries. Using significantly less material than standardized building elements there are significant challenges in their materialization. We present Voxelcrete, a discrete, voxel-based, reconfigurable slip formwork system for the creation of non-standard concrete structures. We aim to transition from highly individualized and complex formworks tailored for individual structures to simple formworks that can be reused and reconfigured to realize a variety of designs. Voxelcrete is a robotically tended formwork system in which modular formwork units are iteratively arranged for continuous casts of concrete. The system allows for the production of large scale concrete objects using reconfigurable, adaptive formwork. This paper shows the conceptualization and development of the system and expands on the existing notion of adaptive formwork*

**Keywords:** *Reconfigurable Formwork, Concrete Construction, Robotic Fabrication, Voxels, Discrete Architecture*

## INTRODUCTION

The construction industry is responsible for high energy consumption, resource depletion, greenhouse gas emission and high waste production. Construction and demolition across the globe contribute roughly 35% to solid waste production a year (Llatas, 2011). A large percentage of the waste itself is material that is ordered for construction yet under- or un-used. The construction of concrete structures is a large contributor to this problem, as specialized single-use formworks are typically necessary during the concrete casting process.

Formwork involved in concrete construction can contribute to up to 35 to 50 percent of the total cost for a construction project with formwork labor as the biggest contributor to this ratio (Peurifoy & Oberlender, 2011). Formwork assembly is often riddled with inefficiencies: lengthy on-site measuring processes, complex assembly logistics and on- and off-site transportation. Ko and Kuo describe formwork

processes as being filled with 'non-value-adding operations and motions' (Ko & Kuo, 2015).

Yet, the amount of concrete construction is continuing to increase. Concrete is utilized for building construction because of its high durability, structural strength, good fire resistance, high sound and thermal insulation properties, and its ability to be engineered for varied applications (Meyer, 2009). The casting process during on-site construction or prefabrication enables the creation of concrete building elements with complex geometric features. Furthermore, utilizing novel digital fabrication techniques and structural simulation methods allow architects to increase the overall efficiency of structures while minimizing the total amount of concrete used (Liew et al., 2017).

However, traditional means of construction in concrete do not allow for this geometric freedom and generally favor the creation of rectilinear elements with inefficient material usage. The construction of optimized freeform concrete structures requires specialized formworks for the concrete casting process, which tend to be disposed of after construction.

Multiple research projects across industry and academia are curently addressing the issues of environmental impact and cost of concrete construction while leveraging the unique design affordances that the material offers. Recent developments in digital fabrication and computational design have allowed to significantly expand the catalogue of approaches beyond traditional construction techniques. This paper presents an addition to the current repertoire of concrete formwork through the introduction of a robotically-tended distributed discrete reconfigurable formwork, prioritizing reusability, low waste, low cost and high design flexibility (Figure 1).

## STATE OF THE ART

The research presented in this paper lies at the intersection of two fields of inquiry: concrete casting of complex geometries and applications of discrete materials.

### *Formwork*

Traditionally, concrete casting in construction is concerned with in-situ production of relatively simple geometries: walls, columns, and slabs. The simplicity of these elements allows to use sheets of material for formwork assembly, providing a relatively efficient and reusable formwork construction method. However, in designs where unique complex geometries are required or would enable lighter and structurally more efficient building components, sheet materials become insufficient. A variety of methods for production of complex geometry formworks have been developed in order to address this, including subtractive and additive fabrication processes, as well as approaches featuring reusable and embedded formwork elements. However, the prefabricated formwork solutions require expensive shipping to the construction site and can usually only be used as one-offs inside a structure

**Subtractive.** Wood-based products and Expanded Polystyrene (EPS) are common materials used for the creation of formworks using subtractive methods. With both materials, waste is created through the milling process and through disposal of the molds as they are generally non-recyclable after use. Some advanced research on robotic hot-wire cutting of EPS focuses on the use of less concrete in order to decrease environmental impact rather than on decreasing waste of the formwork itself (Søndergaard et al., 2019).

Other research is focused on the investigation on alternative materials for formworks that can be recycled in the fabrication process. Wax and ice are two of such materials which are being investigated as substitutes (Oesterle et al., 2012; Sitnikov et al., 2019). Although due to the highly specialized material characteristics of both, issues of scalability and environmental control limit the application of such formworks.

**Additive.** Additive manufacturing techniques have been implemented in order to address ecological impact of concrete construction. The 3D printing of concrete generally removes the need for formwork and therefore reduces the amount of waste, however

Figure 1
Initial Voxelcrete robotic fabrication setup involving truncated octahedron voxels and industrial robotic manipulator

often runs into issues when considering reinforcement. Although various research efforts exist exploring reinforcement as it relates to the 3D printing of concrete, there is still limited industrial application on a building scale of such techniques (Nerella et al., 2018; Zeiba, 2019).

Additive Manufacturing is also being used to 3D print formwork using a range of materials. 3D printing of conventional plastics although widely researched, still produces considerable waste as the plastic is often not recyclable (Aghaei-Meibodi et al., 2017; Jipa et al., 2019). Furthermore, the demoulding process, which is often labor intensive, tends to restrict the geometries that can be made with 3D printing plastic. In order to solve this issue of low geometric complexity, dissolvable 3D printed formworks are currently being researched (Doyle & Hunt, 2019; Leschok & Dillenburger, 2019). Printing of formwork using recyclable material including, wax or clay, is also being tested as ecological alternatives to plastics (Gardiner & Janssen, 2014; Gaudillière et al., 2019).

**Fabric.** Fabric formworks are also currently being investigated for their application as concrete casting due to their low material usage (Veenendaal & Block, 2014). Research on fabric formworks ranges in scale from façade panels to columns to small pavilions (Veenendaal et al., 2011).

Inspired by slipforming, a concrete casting process originally created in the late 1800s, Smart Dyanmic Casting is a novel approach to creating cus-

tomized columns (Lloret et al., 2015). An industrial robotic arm holds an adjustable formwork endeffector, which is moved in the vertical direction as the concrete cures. Through adjustment of the end-effector, the cross section of the column can be changed dynamically.

Highly complex fabric formworks are also currently being manufactured using industrial knitting machines (M. Popescu et al., 2020). With such formworks, concrete is applied to a tensioned knitted formwork which is embedded in the final structure, therefore minimizing waste in the process. The digitally controlled manufacturing process can also embed sleeves or other beneficial attributes for the formwork a single textile element.

Although fabric formworks are a reliable ecological alternative, they customarily require complex tensioning system attached to static geometries, which can limit their application scenarios and scalability.

**Reconfigurable.** Reconfigurability is another approach to fromwork in which formwork elements can be adjusted or rearranged for the creation of varied geometries. Although industrial research tends to focus on formwork solutions for highly rectilinear or single curved structures, academic research expands this approach to include doubly curved surfaces. The scale and resolution of reconfigurable formworks ranges to a high degree. PERI formworks [1] for instance functions on the scale of entire walls or slabs while Kine-Mould works on a scale of two by two meters (Schipper et al., 2015).

### *Digital Materials / Discrete Architecture*

The materialization of discrete structures is also being reconsidered from a broader design perspective in architectural discourse. Borrowing the notion of digital materials, or materials with a finite set of parts with pre-defined connection possibilities, discrete architecture attempts to build highly differentiated structures using a kit of serial parts (Gershenfeld, 2012; Retsin, 2016). Using set of computer-generated rules, the parts can be assembled, dissembled and reassembled to form different configurations. As such, discrete architecture is attempting to redefine the production chain of architecture tackling issues of efficiency in construction (Retsin, 2020).

Varied approaches and methods to validate discrete architecture at different scales have been developed within the last decade. Rossi and Tessman developed a computational framework for designing structures based on discrete elements considering robotic fabrication constraints (Rossi & Tessmann, 2017). Various video games have been developed in order to question the nature of crowd sourcing design using discrete logics (Sanchez, 2018; Savov et al., 2016). Jonas et al. developed strategies for top-down approximation of geometries and bottom-up generation of structures using a kit of parts (Jonas et al., 2014). Focused on scaling up, large scale timber modules are being developed in both digital and physical experiments (Retsin, 2019). Although small housing units have been constructed, major concern is expressed with the high number of connections and thus accumulation of stresses when considering discrete architecture at a large scale.

## METHODS

In considering sustainability, economic and geometric flexibility factors, this paper introduces *Voxelcrete*, a distributed voxelized reconfigurable formwork system. The formwork system, taking notes from digital materials and discrete architecture, is composed of a kit of voxels with defined connectors. Voxels can be arranged to form closed containers into which concrete can be casted. The voxels are then rearranged relative to the curing of the concrete in order to allow continuous pouring, comparable with the traditional formwork approach of slip forming. Once an area of concrete that is poured from above is cured, the voxels around it are free to be rearranged as diagrammed in Figure 2. This process is robotically tended, allowing for it to be done at run-time, considering the current state of the material and the desired geometry of the final object.

*Voxelcrete* allows for the creation of continuous self-supporting concrete structures at ranging reso-

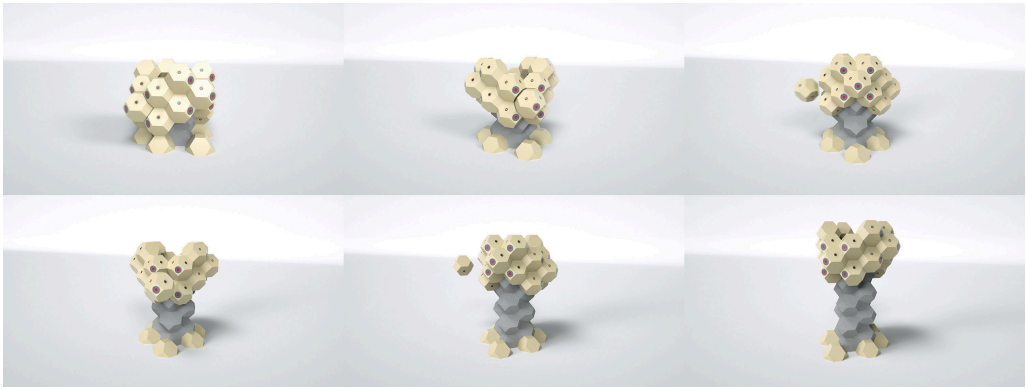

Figure 2
Diagrammatic representation of construction with Voxelcrete.

lutions and scales using a fully reusable formwork system.

### *Experiments*

The initial experiments aimed at developing a discrete material system, as well as computational and robotic methods for *Voxelcrete* in order to produce a load bearing column.

The truncated octahedron was selected as the shape of the discrete material voxel unit. The voxel therefore has fourteen connection surfaces allowing for a large quantity of aggregation possibilities and the ability to transfer vertical loads between units. The truncated octahedron can also be packed at higher densities as compared to other voxel shapes therefore allowing for zero gap aggregations (Kim and Lee, 2015). This allows for the addition of voxels in order to strengthen concrete containers depending on the hydrostatic load during concrete curing. Due to the angularity of the shape, the vox-

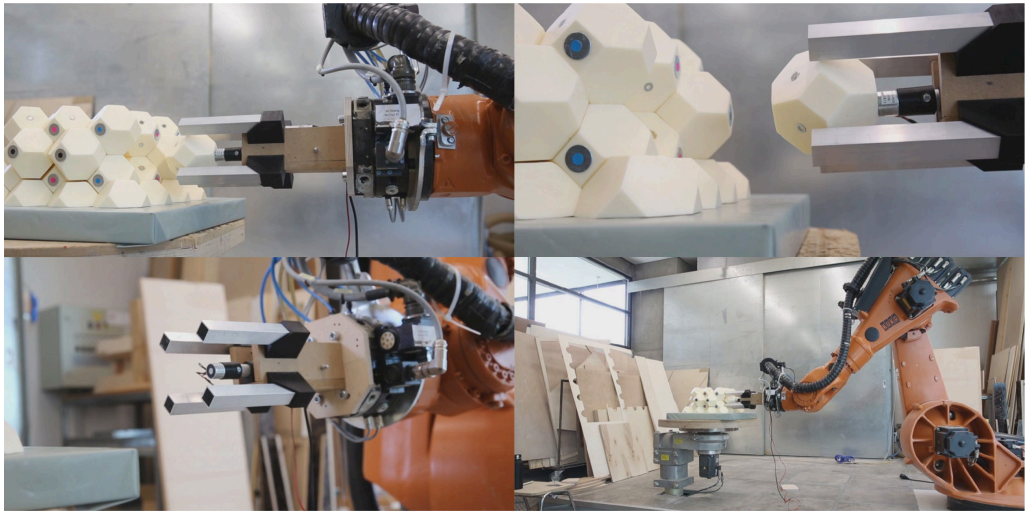

Figure 3
Rearranging voxels with KUKA KR125

els notch into each other and nestle into previously casted concrete in order to minimize slipping due to gravity. For the purpose of the first experiments voxels were wire-cut from EPS. High strength magnets were embedded on the sides of the voxels to join them together. The voxels were further lubricated on all slides in order to allow for minimal cleaning during their continual reuse in the fabrication process.

An industrial robotic arm, KUKA KR 125, was chosen as the robotic agent to assemble and rearrange the voxels (Figure 3). A custom end effector was designed to interface with the truncated octahedron voxel. The effector combines a linear actuator and electromagnet, to successfully attach and detach voxels from one another. The 6-axis industrial robotic arm, although limited in work environment, provided a suitable platform for testing the automation of *Voxelcrete*.

Methods for designing discrete assemblies are currently becoming available to designers as plug-ins to existing 3D modeling software (Rossi & Tessmann, 2017). Computational methods developed for *Voxelcrete* focused on deriving fabrication logics for predesigned structures. Custom developed software, displayed in Figure 4 initiates by designers express their intent for a target geometry using splines and thickness values. This target geometry is then populated with truncated octahedron voxels. It is sliced into sections in which voxel containers are defined to allow for concrete pouring from above. The software finally calculates the repositioning of voxels from one container position to another by minimizing the distance each voxel travels and writes that into robot control code. Arrangement of the voxels is informed by their truncated octahedron shape, with the outer most voxels being rearrange first.

Digital experimentation involved the development of the computational software to produce reliable robotic control code for varied geometries, including columns, walls and slabs (Figure 4). In order to understand, the implications of the physical system on the output geometries more experimentation would need to be conducted.

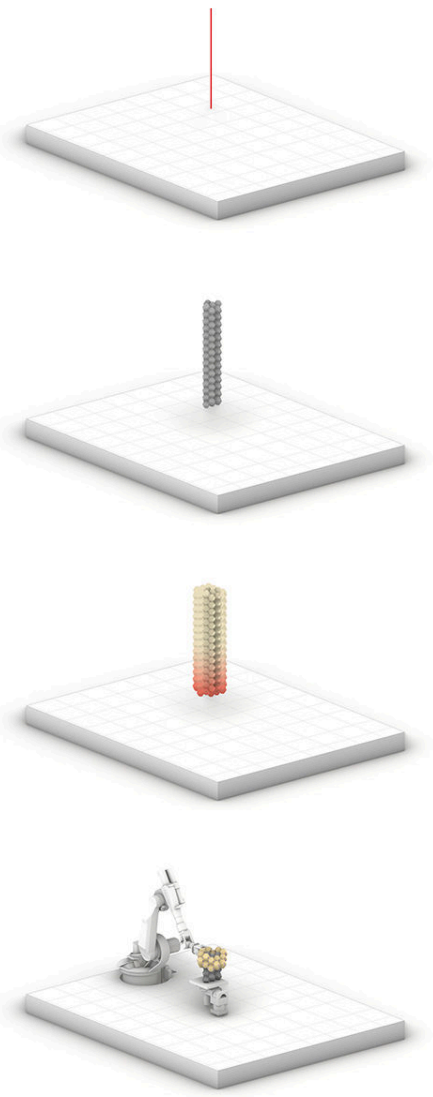

Figure 4
Diagramatic representation of computational worlflow (top to bottom): user defined spline, voxelized geometry at user defined thickness, container creation, and robotic control code generation.

Figure 5
Results of initial physical experiment

## DISCUSSION

Figure 5 shows the results of initial experiments in which twenty-four EPS voxels were robotically arranged and manually filled with concrete. A lthough initial experiments proved successful, the optimal materialization of *Voxelcrete* is still being evaluated.

### *Reusability*

*Voxelcrete* is a reusable formwork system that can be implemented in diverse environments. Minimal site preparation and infrastructure are required for it to function. Voxels can be utilized on one construction site and then transported to another in order to be used again. Although the recyclability of the current voxels after extensive use is unknown, the voxels are cheap and easily manufactured. Waste is generated only through the degradation of voxels after multiple cycles of use and re-use.

### *Robotic Automation*

The current deployment of the modular formwork is limited by the reach of the industrial robotic arm. Concrete structures can only be designed within the work envelop of the robot. However, the design space could be extended through implementation of mobile and/or distributed robotic systems. A robot arm installed on a rail or a mobile platform would significantly increase the work envelope of the system (Dörfler, 2018). Furthermore, small mobile task-specific machines could be deployed with the *Voxel-*

*crete* material system. Recent developments in tasks-pecific and climbing robots acutely outline the potential of these systems for in-situ fabrication (Jokic et al., 2015; Leder et al., 2019). As the voxels are generally light weight, envisioning small machines to detach voxels and reattach them in new locations is fully feasible. Specifically, one could speculate on a custom robot that walks on already printed concrete and another robot that is responsible for supplying concrete tasks.

### *Resolution and Scale*

Deploying such distributed robotic systems for the arrangement of the voxels would allow for the resulting concrete structures to grow in all directions. Reinforcement, however, would need to be integrated into the system in order to allow for the growth on a building scale. The development of rebar voxels to be added to the kit of parts is one solution to reinforcement that could be tested for *Voxelcrete*. The step wise multi-layer pouring of concrete allows for the continuous embedding of reinforcements across the whole structure.

Further development of the kit of voxels could address the resolution at which *Voxelcrete* is executed. Larger voxels would allow for a more efficient process at the cost of detail resolution. Truncated octahedrons are limited to the fourteen faces in which they connect to each other. Thus, extending the catalog of voxel geometries beyond the truncated octahedron would result in a wider range of possible textures and resulting structure geometries.

Effective scaling of the system is dependent on the connections between the voxels. Resisting hydrostatic load during the curing of concrete is a common challenge for formwork systems. Although layering of voxels can increase the holding capacity and initial experiments prove the feasibility of the *Voxelcrete* system, the strength of the connections relative to loads from the curing concrete need to be address in order to fully validate the system. Potential solutions include implementation of stronger magnets or development of mechanical locking systems.

## CONCLUSION

Recent investigations on reconfigurable formworks are attempting to address the environmental impact of concrete. Current reconfigurable formwork systems are allowing for the construction of rectilinear structures. However, when considering optimized architectural forms that would allow for a significant reduction of concrete use, single-use and highly expensive custom formworks are being utilized. *Voxelcrete* presents a novel fabrication approach in creating a reconfigurable, reusable, discrete slipform concrete formwork for freeform geometries. It bridges the gap between conventional formwork techniques and novel robotic fabrication techniques, utilizing the principles of digital materials and discrete architecture. The approach has implications on the automation, efficiency, waste production and overall cost of concrete construction.

*Voxelcrete* enables continuous production, unrestricted by scalar or temporal limitations. This allows for the construction of highly varied designs created by architects using current design technologies without excess amounts of construction waste. Initial experimentation shows promising results that self-supporting concrete structures can be generated using *Voxelcrete* at a small scale. Additional research is needed to fully automate and validate the system for larger structures.

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# Source Material Oriented Computational Design and Robotic Construction

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*The disconnection between architectural form and materiality has become an important issue in recent years. Architectural form is mainly decided by the designer, while material data, for example, the natural shape of source materials, is often treated as an afterthought which doesn't factor in decision-making directly. This study proposes a new, real-time scanning-modeling system for obtaining material information, and incorporating the data into a continuous digital chain of computational design and robotic construction. After collecting and visualizing the data, the calculation portion of the chain processes the selection of source materials and generates architectural geometry based on both human-designed rules and various shapes of materials. Finally, at the action end of the chain, an industry robot is used to fabricate the design. End-effector is designed for tightly gripping the irregular source materials. Scripts is written in Grasshopper for positioning the components and assemble them into configurations. This study also shows a pavilion developing with the continuous digital chain*

**Keywords:** *scanning-modeling system, source material information, computational design, robotic construction*

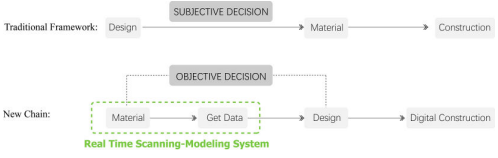
## MOTIVATION AND GOAL

The disconnection between form and material in architecture field has become a serious problem. With the popularity of 3D modeling software such as SketchUp, Rhino and Grasshopper, architects are prone to first develop form on a computer screen, (KaicongWu&AxelKilian,2018)and only afterwards associate material designations to the predefined geometry model. In this way, the digital form is freely rendered with any material bitmap or texture without regard to a material's rational use or practicality, and risking that material information cannot be timely and effectively fed back to the design and construction stages. (ArtemHolstov,Graham Farmer&BenBridgens,2017)

The separation of material and form has caused some problems in recent decades. Firstly, in most design and construction workflows, raw material is assumed to be transformed into a variety of sizes and shapes through industrial processes in accordance with computer-derived geometries instead of relying on these materials' natural geometries. This process consumes significant time and material, while producing waste. Secondly, it diminishes the archi-

tectural and experiential qualities of materiality. As material properties aren't fundamentally integrated at the start of design, the architectural form, unrestricted in digital space, develops independently of the weight, thrust and resistance of materials, (AntoinePicon,2004) leading to the loss of the physical dimension and perceived physical experience of architecture. Thirdly, the gap between design and construction becomes wider, especially in projects with irregular surfaces and complex geometries. Ignoring a raw material's unique properties makes the fabrication process more passive, inefficient, imprecise and expensive. Finally, the separation of form and material leads to the increasing homogeneity of architecture. Materials with different characteristics are mass produced through the same processing method. Materials tend to be used superficially or for singular effect, while their other attributes are often ignored or suppressed.

Advances in contemporary digital scanning and bespoke robotic technologies(GramazioF et al,2005-2013;Gramazio&Kohler2014), however, enable material information to be simulated, calculated, and well organized, resulting in designs derived not only subjectively by the architects but also objectively by the material itself. In this paper, we introduce a new, real-time scanning-modeling system for obtaining material information, and incorporating the data into a continuous digital chain of computational design and robotic construction(see Figure 1)




The scanning-modeling system is treated as the sensing end of this digital chain. It reads data of source materials including their sizes and shapes without cumbersome supporting equipment and builds a visual model in real-time. After collecting and visualizing the data, the calculation portion of the chain processes the selection of components and generates architectural geometry based on material data, site conditions, structural performance and human-designed rules. Finally, at the action end of the chain, an industry robot would be used to fabricate the design. Camera-based sensing is developed for robot localization within the construction site. Together with the data obtained from material sensing stages, path-planning of the robot arm could be programmed for positioning the material components. In sum, this study creates a convenient and rapid material information acquisition system that benefits architectural design and digital construction.

## LITERATURE REVIEW AND INNOVATION POINTS

This study provides a new scanning-modeling system and examines its application in architectural programs. The research contents include autonomous perception, computational generation, and robotic actuation. Despite a great deal of research on these three topics over the past several decades, there has been very little research intended to integrate them in the field of architecture. Previous studies and new development in measuring and modeling, computational design, and robotic construction are described as follows.

### *Measuring and Modeling*

Existing 3D reconstruction methods can be divided into two categories: active and passive. The active methods mainly include Moire Fringe, Time-of-Flight (ToF), and Structured Lighting and Triangulation; while the passive methods mainly include Shape From Texture (SFT), Shape From Shading (SFS), Multi-View Stereo (MVS), and Silhouette. "+" means the performance is strong while "-" means it is weak. These methods usually combine mathematical and physical knowledge. Among them, Moire Fringe uses the interference of wave to deduce the shape; SFT, SFS and Structured Lighting mainly use perspective principle; Triangulation, MVS and Silhouette use the methods of deformations of triangle positioning. The characteristics of each method are presented in Table

Figure 1
comparison of two modes

1. (R.Zhu,2014;J.Schlarp,2019) "+" means the performance is strong while "-" means it is weak.

Table 1
Measuring and modeling methods

| | Name | Principle | Speed | Accuracy | Cost | Stability | Limitation |
|---|---|---|---|---|---|---|---|
| Active Method | Moiré Fringes | Diffraction and interference of light | ++ | +++ | + | + | only available for objects with regular texture |
| | Time-of-Flight (ToF) | time taken for the wave to bounce back to the emitter | ++ | -- | -- | - | Low resolution and easy to be disturbed |
| | Structured Lighting | Encoding and decoding of light | + | ++ | + | ++ | Projection equipment required |
| | Triangulation | Solve trigonometric equation | + | - | + | + | Data sparseness |
| Passive Method | Shape From Texture (SFT) | Perspective distortion calculation | + | + | + | - | Surface texture information required |
| | Shape From Shading (SFS) | Ray calculation | - | - | + | - | Light parameters required |
| | Multi-View Stereo (MVS) | Parallax principle | -- | -- | + | + | Image error is big |
| | Silhouette | Visible shell approximation | +++ | -- | ++ | ++ | Visible shell only |

The scanning-modeling in this study would be manipulated on construction site, except for measuring accuracy, stability, speed, convenience and flexibility should be taken into account as well. With general consideration of all factors, this study is established on the basis of silhouette method, which we develop to improve the speed and efficiency of getting information on material size and three-dimensional shape, and to make it easier to operate as the computing and information communication mechanism are in a visual interface.

### *Computational Design*

Different from design precedents which rely on intuition and experience to solve design problems, computational design encodes design decisions using a computer language, so design expression is changed from geometry to logic. (H.Hua,2017) Computational design is excellent in dealing with complexity, coming up with many options in a short time, and optimizing the solution. Although computational design is still a relatively young and evolving field, (GiulioBrugnaro et al,2016) some research institutions and researchers have made progress in theoretical development, methodologies and strategies.(P.Eversmann,2017;M.Larson,2019)

Based on the methodologies and strategies of computational design, this study presents a pavilion which is generated from source material information. The major dimensions of computational design in this study include: 1) Information transformation: this pavilion makes use of naturally grown branches containing three forks. The length of each fork, and the angles between the forks are read by a scanning system and the information is transformed into Grasshopper in real time by a plug-in we developed. 2) Parameter setting: considering the site conditions and the pavilion's functional uses, the parameters we set are the location of the anchor points, the camber of the surface, the fractal geometry, and the number of forks at a node. 3) 3D modelling and visualization: the computation of the design and fabrication is conducted in Rhino3D which allows designers to test and simulate in a visual environment. 4) Processing with data and algorithms: The rules and standards to inform the design direction comprise wasting less material, similarity to the target surface, and structural performance.

### *Robotic Construction*

The use of robots in architectural construction can be traced back to the 1980s. (JoséPedroSousa et al,2016) At that time, robotic systems were mainly used in Japan, but the efficiency didn't prove satisfactory and hence received fading research attention. However, with the development of digital tools and manufacturing technologies, robotics in architecture has been a burgeoning research topic since 2010. Prior studies have sought to explore and expend the feasible scope of robotic fabrication, including effector tools, human-computer interaction, path-planning algorithm, etc. But an important limitation of past research is the material sensing and real-time feedback. This study seeks to fill that gap by emphasizing robotic eye-hand coordination, and to break with the typical robot movement pattern which is controlled by humans and not by the robot itself.

## REAL TIME SCANNING-MODELLING SYSTEM

### *Framework*

The procedure of The real time scanning-modeling system is shown as Figure 2. For each material component, the images from different perspectives will

be scanned by camera group. An independent program specially written by this study will capture the effective information of the material image and calculate feature points using an open source computer vision library. In order to ensure operational and data transmission efficiency, the program is simplified to transmit data of the quantity of controllable feature points with high information concentration. Then, a pre-programmed plug-in in Rhino/Grasshopper will receive data from the scanning program by memory mapping and analyze outlines from different perspectives. Finally, a three-dimensional model of the corresponding material component will be generated within 1 second for subsequent design development.

This paper takes natural branches as an example material to explain how the scanning-modeling system works. The system extracts contours of the physical branch and reconstructs it digitally. It has two working paths: a software workflow and a hardware workflow. The software workflow is virtual and processable, while hardware workflow is realistic and transitive. The data circulate and transmit in the software workflow, participating in complex interactions and transformation operations, before finally outputting a concise digital model of the branch. The hardware workflow is very simple, consisting only of material components, sensors (cameras), and a computer. Six cameras can complete all of the image acquisition work, while the computer can realize image recognition, data processing, and 3D model reconstruction.

### *Hardware workflow*

The branches (source material), camera group and computer constitute the hardware workflow of the system. In the laboratory, we build a 6m-long custom frame to fix the cameras, and cover the background with black curtain to extract information effectively. The conditions and settings for each hardware element are as follows.(see Figure 3, Figure 4)

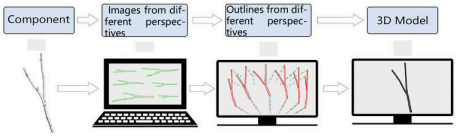



Figure 2
Scanning-modelling system

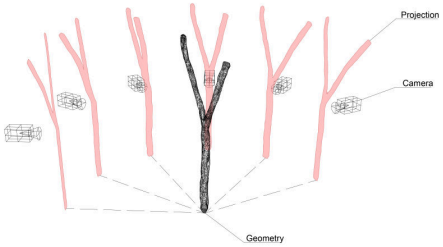



Figure 3
Methods of hardware

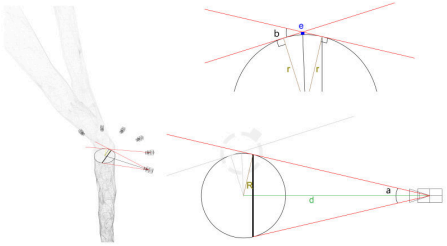



Figure 4
Calculations

**(1) Branches to be tested:.** This study used natural branches which had minor branches, leaves and twigs pruned away. Their lengths range from 75cm to 245cm, and their radius range from 2cm to 10cm.

**(2) Number and location of cameras.** The branch's radius is set as R, the length of the frame holding the cameras as L, and the camera angle as a. An equation can be calculated:

$$L = 2\frac{R}{\sin\left(\frac{a}{2}\right)} \quad (1)$$

The number of pixels in the corresponding direction of the camera is set as n, the resolution value of the reconstructed model is y. Calculation is based on the 1st formula:

$$y = 2R\frac{\cos\left(\frac{a}{2}\right)}{n} = L\frac{\sin\left(a\right)}{2n} \quad (2)$$

The inherent error of this system is that it is not uniform. It is affected by two factors: one is the angle between the object and the camera, and the other is the normal vector of the surface point with respect to the plane of the camera group. To establish this error, this study sets the angle between two adjacent cameras as b and the inherent error as e. An equation can be calculated

$$e = r\left(\csc\left(\frac{b}{2}\right) - 1\right) \quad (3)$$

In order for y> e, and considering feasibility, convenience, and accuracy, we finally take L = 600cm, a = 0.3π, b= 0.667π, which means, 6 cameras are fixed to a 600 cm-long frame to catch images of the branch.

### *Software workflow*

The software workflow is the core of this system. It includes three steps:

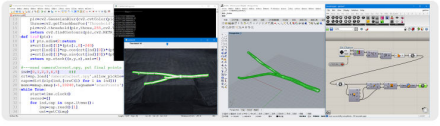
- (1) generating a description file of calibration cameras
- (2) An external program which extracts the image of the branch and calculates related data for visual presentation.
- (3) A pre-programmed module in Rhino receives the data and converts it into a digital branch model in real time. The following sections explain the three steps in more detail.

Figure 5
Software workflow

The first step is to develop a camera calibration file "CameraCorrect.py". The purpose of this step is to determine the mapping relationship between contour pixels and spatial points in the modeling software. The calibration is based on the perspective principle, it does not require a complete camera internal parameter matrix, only a scaling parameter and rotation parameter are taken. Because of the USB broadband limitation, an additional module was added in the Python script in order to read information from multiple cameras simultaneously. There are five commands "z", "x", "f", "s" and "q" in the script: "z" and "x" to change the camera, "f" to refresh, "s" to display the recorded data, "q" to save the data and exit. After the relevant parameters of the calibration tool are entered, an auxiliary script automatically calculates the final calibration parameters and generates this calibration file. This step only runs once in whole workflow and is not repeated every time a branch is scanned.

The second step is to analyze the branch images and generate both a "Points.py" file which contains image information and a "getGeo.gh" file which is used in the modeling software. First, through Gauss filter process and binary image process, it is able to extract smooth contours of a branch in different perspectives. Then, the number of pixels selected in the contour is adjusted by a tolerance parameter and the three-dimensional coordinates of all the selected points are calculated. Finally, the three-dimensional array is transferred into Grasshopper through shared memory, and the spatial position of the points is inversely mapped in Rhino according to the former calibration file.

The third step in the software workflow is to generate a visual model which runs simultaneously with the second step. A preset program receives array data and reorganizes them into projections from different views in order. By the algorithm of Boolean intersection, all the information work together to generate a digital branch model representative of the scanned physical branch.(see Figure 5)



**3.4 Features and new innovations.** The system is characterized by flexibility, reliability and processing speed. Because of the modular organization of the workflow, the perception of material information is expandable. We can increase the number of cameras to improve the accuracy of the system, and we can also expand the type of sensors to capture and ana-

lyize other qualities of the source material. Flexibility is also reflected in the diversity of operating environments and source materials. Although the former branch experiment is carried out in a laboratory, it can be performed in other places including outdoor environments by simply changing the fixing points and corresponding values in the equations. Similarly, the system can scan other building materials (source materials). Additionally, the system has a high tolerance for faults, with built in redundancy, and therefore is very reliable. Even if some of the sensors are broken, other sensors can still work as usual, so the program can run normally despite the reduced accuracy. Finally, this system runs very fast. Usually image processing is extremely CPU intensive, but this system basically eliminates this problem with appropriate abstraction and sufficient optimization. Taking the branch project as an example, even in ordinary notebook configuration, a refresh rate of 1 second per time can be achieved. This efficiency not only saves time, but also makes the system more practical to use.

## APPLICATION EXAMPLE

### *Organization of the Branches and Generation of Pavilion Geometry*

Using the above-mentioned real time scanning-modelling system, we built a pavilion and show the application of the system in new architecture model. This pavilion uses abandoned "Y" shaped branches as source materials. We firstly scan all wooden branches which can be used for the pavilion and their digital models are automatically rebuilt in Rhino/Grasshopper. Next, we distill the information useful to design, discarding data that does not affect the design such as slight unevenness on the branch surface, the bending amplitude of each fork, etc. The useful parameters are: three-dimensional coordinates of the four points-P0, P1, P2 and P3- of the branch, the length between each two points, and the length and thickness of each fork (see Figure 6.). Because all tree branches are from the same species of ash tree, their density is considered the same.

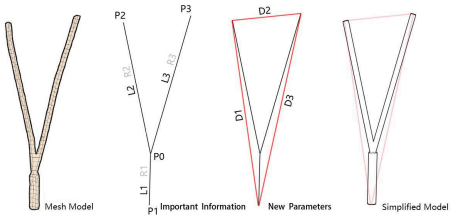



Figure 6
Information abstraction

According to the environmental conditions and functional requirements, we established the approximate dimensions of the pavilion, the location of the ground points, and the geometry logic as a preliminary step, in addition to stipulating that each vertex must have three forks jointing together. We program the rules in Grasshopper/GH Python to generate and optimize the geometry, and to organize the material components. The logics are set as follows: 1) All branches are sorted by volume, and the three largest load-bearing branches are selected. 2) For any two branches B and C which are connected to the same Branch A, if they can intersect, their intersection trajectory is an ellipse and takes the position with the minimum distance from the central axis of branch A to ensure the overall stability. 3) If Branch B and Branch C cannot intersect, they are cut shorter to make the intersection possible. According to the information list of all the branches, the computer can quickly calculate the cutting lengths of different options and the branches spatial positions under all possibilities. Corresponding pavilion forms are also simulated and all possibilities are sorted by how much material is wasted. 4)The top five options are chosen, then "millipedes" and other analysis tools are used to test and optimize their structural performance. As shown in Figure 7, analysis result shows that with only three load-bearing branches, the shear force at the grounding points would be very strong and may exceed its beating capacity. So three more grounding points are added and the upper part of the geometry is adjusted to make force distribution more uniform and reasonable. Combining the amount of material waste factor, structural

properties and formal aesthetics, the final pavilion design option is selected.(see Figure 8)

Figure 7
Computational generation process

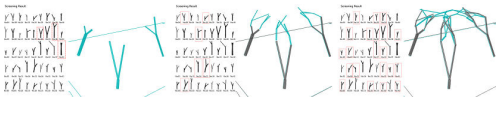
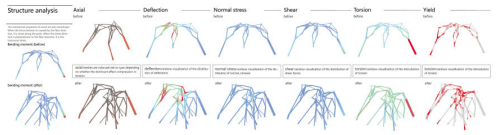


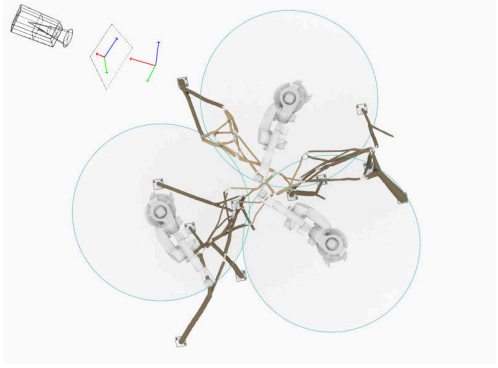
Figure 8
Structure performance analysis



## *Zoning and Robotic Localization*

At the beginning of robotic construction, the project encounters a problem: the scale of the pavilion is larger than the reach of the robot arm. Generally, this problem can be solved with mobile platform or multi-robot cooperation. But our laboratory does not have such equipment, so we take an alternative "self-cooperation" approach. We divided the pavilion into three operating areas, and each one is within the robotic armspan. As in Figure 9 shows, the robot is placed in three locations in turn to complete the work of each area.

Figure 9
Self-cooperation



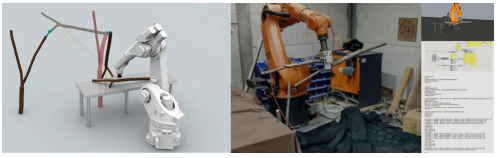
After replacing the robot, it must "know" its own position if it is to localize itself and to manipulate its surroundings. We set a reference in the construction site to anchor the coordinate system. The reference frame is like XYZ axis, extending a fixed length rod in three directions perpendicular to each other. The camera-based sensing system can observe the reference, and calculate its position according to the length of the three coordinate axes in the image. With the alignment between the sensing reference and the robot, the robot localization achieves 2cm positioning accuracy.

## *End Effector-designing and Path-planning for Grasping and Positioning Branches*

In the robotic construction stage, the design of the end effector and planning routines of the robot arm should be carefully considered. In terms of the end effector of robot, it has to be strong enough to grasp the branch, ensuring it doesn't twist. We first tried an electronically controlled claw. With the AFMotor library in Arduino, the opening and closing state, running speed and rotation direction of the gripper can be controlled in real time. However, such claws have limitations: its opening and closing range is only 0-90mm, and its maximum clamping force is only 16 newtons, so it is only suitable for grabbing light and small branches.

In order to improve the grabbing ability, we later select and modify the pneumatic parallel open/close claw. The size between the parallel plates could be adjusted to match the diameter of the branch. The contacting surface of the plates is coated with a special rubber material to increase the coefficient of friction so the branch wouldn't twist. Features of this pneumatic claw are: 1) Wide opening and closing range. 2) Greater grabbling ability. 3) Suitable for branches with different sizes and weights. 4) Can be deployed in GH, so the robot arm can perform the entire step independently.(see Figure 10)

Figure 10
End Effector Designing and Path Planning



In terms of path planning, iterative method is used to prevent the potential collision accidents in the construction. For each movement, the starting point of the iteration is the line formed by the two endpoints of the path. The original line will be divided into several segments by some control points to provide it the possibility of change. Then the program will detect the collision of each segment. If got true, the control point will be "squeezed out". This process will be repeated until all segments are negative. Finally, the curve is the proper path. In addition, due to the posture adjustment involved in the actual path, we set up three interlocking virtual paths for each actual path in order to solve the results

In this study, feature points are used to locate components. For each "Y" shaped branch, we use convex hull and clustering techniques to calculate its three endpoints and a center point, and then build a "Y" shaped skeleton. In order to ensure the stability, we take nearly 1 / 3 of the long rod as the grab point, and determine the grab posture according to the long rod direction and the "Y" fitting plane. A plug-in of Grasshopper - KUKA | prc - is used for computing the control data of each axis of the manipulator based on the dimensional values. Thus, the robot can grab the component, control moving trajectory, and find position for assembly.(see Figure 11)

### *Joints-designing for Feedback Error Correcting*

During the robotic construction, errors are accumulated layer by layer. The last and not the least important step is the error control. At present, there are usually two methods to deal with errors: reducing errors through higher precision control, or designing structures with larger error redundancy to directly absorb errors. Considering the complexity and reliability, this experiment adopts the later strategy. A special node with universal joints, three-way pipes and jackscrews is designed to share the major error.

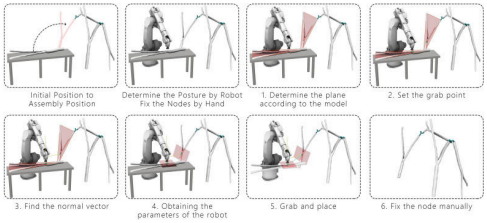



Figure 11
Positioning branches

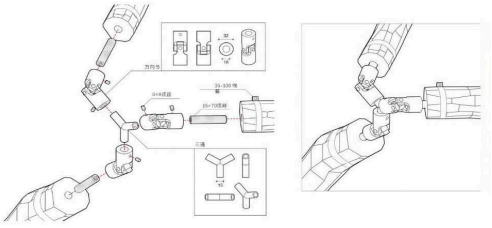


Figure 12
Joints

The universal coupling is very flexible and can freely adjust the distance and angle of the two connection points. Before positioning the branches, the cardans are fixed on each branch. As shown in Figure 12, each pipe with a universal joint will be fixed with a fork, and there are three universal joints in each node. They are connected by prefabricated metal pipes instead of traditional shaft. Moving the branch to corresponding position is done autonomously by the robot, while welding the cardans and locking the node is accomplished manually by architects. In this way, all errors are concentrated at the nodes and guarded firmly there, avoiding any impact on the structure or the subsequent construction.(see Figure 13, 14, 15)

Figure 13
Joints

Figure 14
Pavilion

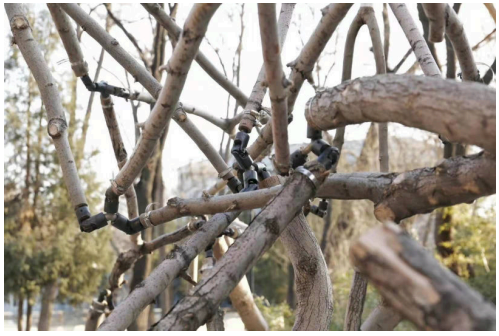


Figure 15
Pavilion

## CONCLUSION AND FUTURE WORK

This study uses a real time scanning-modelling system to perceive and analyze source material geometry, and then guides the robotic arm to complete the construction work based on the generative design. The material oriented "eye-brain-hand collaboration" chain saves construction materials, greatly reduces the cost of component fabrication, gives unprecedented flexibility to geometry, optimizes structural performance, and improves construction work.

This study still has great potential for improvement. Though possible in theory, more testing should be made to prove that the scanning-modeling system could be used not only for branches, but also for other architectural materials with irregular shapes. Future work could also expand sensor types and algorithms to perceive other information such as toughness and texture of the source material. Besides, in construction stage, heavy industry robot could be replaced by mobile robot for on-site manufacturing, assembly and digital fabrication.

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# Robotic Swarms in Architectural Design

## *A communication platform bridging design analysis and robotic construction*

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*The research work fueling this paper examines optimal approaches for bridging design analysis and robotic spatial construction. In this context, the paper presents the development of a unified platform for managing a swarm of robotic fabrication agents. The goal is the development of a streamlined methodology that guides the conversion of a design model into construction data code that can be assigned to the robotic swarm for fabrication.The work focuses on bridging architectural design platforms and distributed automation processes, on the one hand, and on the other, it targets the development of a functional management tool for adjusting and optimizing fabrication. A crucial parameter considered is the monitoring and assessment of all stages of the proposed process. This involves a constant exchange of information between the various actors, such as the swarm agents, the construction data and the designer - user. As a result, the construction process is treated as a constant reassessment and re-adjustment of the design parameters rather than the linear result of the original set of construction data. Therefore, the proposed system cannot be described as reactive, but acts responsively in a ``sensible`' manner.*

**Keywords:** *Swarm Robotics, Adaptive Fabrication, Robotic Construction Communication Platform, Sensible System*

## INTRODUCTION

The paper presents the conceptual framework and preliminary results on the development of a platform that aims to bridge contemporary Digital Design Tools and Robotic Fabrication Methods (Fig. 1).Four individual aspects of the ongoing research are discussed.

Firstly, the paper highlights the main characteristics of the proposed Design Platform Framework. Secondly, two types of Robotic Fabrication Platforms are described. Thirdly, the paper analyzes the conceptual framework of the Fabrication Methodology, that leads to the fourth part presenting preliminary experiments regarding the development of the

robotic platforms. The paper concludes with future directions of the research on bridging Digital Design and Robotic Fabrication.

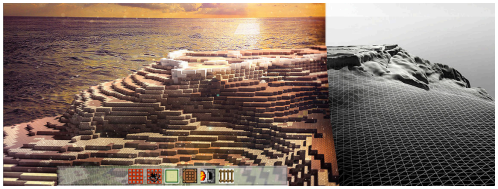


Figure 1
Snapshot of the platform created for managing a Swarm of Robotic Fabrication Agents.

## DESIGN PLATFORM CHARACTERISTICS

The main objective of the proposed platform is to provide an optimized framework for communication between design and fabrication. Specifically, the platform provides a bridge connecting Digital Design Tools and Robotic Fabrication Methods for open terrain, allowing the designer to directly communicate with the robotic fabrication units and guide effectively a dynamic construction process.

The design platform defines Building Blocks for achieving spatial transformation through the analysis and utilization of environmental and geomorphological data. As a basis for this approach, the Minecraft software environment was selected. Minecraft provides a new way to represent an environment through discrete cubic elements. These elements can be assigned with different material properties. Users can then utilize the elements in order to assemble complex structures. The Minecraft platform is easy to use, requiring little or no programming skills, in order to be modified according to specific requirements. Furthermore, the software's versatility allows for the development of different scenarios and the introduction of machine-learning algorithms. Thus, a large number of experiments can be conducted in a short time period (Aluru et al 2015).

Therefore, instead of creating a new software from scratch, the proposed platform operates as a plugin in Minecraft, taking advantage of the aforementioned characteristics. Furthermore, it provides tools to translate the design information into fabrication data for the robotic units. By describing the design as blocks, it is able to reduce the complexity, requiring less computational power during construction, while remaining true to the original model. Finally, the ability to simulate the environment allows for the integration of the relevant parameters in the early design phases.

## ROBOTIC FABRICATION TOOLS

The second aspect of the present work is the utilization of robotic fabrication methods in conjunction with the aforementioned platform. The use of robotic means in the field of architecture has been on a continuous rise during the past 20 years (Kamimura et al 2001). This proliferation leads to a corresponding increase in the number of applications in which the field of robotics may create new opportunities for synergies within the design process (Brell-Cokcan & Braumann 2013). There are multiple benefits to the utilization of robots in design, since they can consistently perform roles within controlled environments (Corke 2013) (Fig. 2).

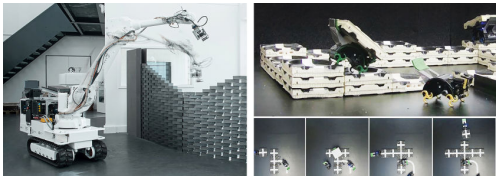


Figure 2
(Left) In Situ Fabricator [1] (ETH Zurich 2017).
(Right) TERMES Project [2] (WYSS Institute 2014).

The method utilized in the context of the proposed framework is based on practices from the field of swarm robotics. Designers are already employing small robotic swarms that allow design flexibility (Sahin & Spears 2005). These have been mainly employed within controlled environments and following simplified set of commands. However, when scaling up this approach to a non-controlled environment and through an increased complexity in design, robotic swarms are faced with increasingly complicated tasks that require them to be deployed in large numbers.

The deployment of robotic swarms in environments of increasing complexity requires the development of new algorithms as well as new, enhanced de-

sign tools. Relevant research focuses on three main areas. The first one is based on Brooks' approach and guides the increasing of the accuracy of the robotic swarm (Brooks 1989). The second is directed towards improving the detail of their programming (Gramazio et al 2014), while the third one allows for better utilization of the design model (Achim et al 2017). To facilitate a better understanding of the concepts discussed, two such case studies are briefly presented: the *In Situ Fabricator* (Gramazio & Kohler 2014) and the *TERMES* project (Petersen et al 2011).

### *In Situ Fabricator Mobile Robotic Unit*

The Digital Fabrication of the *In Situ Fabricator Mobile Robotic Unit* (Fig. 2), developed at the National Centre of Competence in Research (NCCR), consists of an industrial robotic arm placed on top of a mobile robotic platform. What is of special interest is the fact that the robotic unit is equipped with 3D scanning devices and sensors. These sensors constantly provide the robotic unit with data regarding the environmental setting in which it operates. Therefore, the robotic unit is able to adapt in real time to changes in its environment. The fact that robotic platforms are able to receive, filter and act upon real-time data received during the construction task, eliminates the need for adjustment to the operating environment. This allows for future deployment of similar platforms in construction sites.

The integration of sensors on robotic construction platforms significantly expand their capabilities, paving the way for an enhanced, yet seamless collaboration between humans and robots. This initiates a dialogue in which the robot -having a certain level of autonomy- takes independent decisions based on the data received by its sensors (Fig. 2). Additionally, the robot is able to provide data to the designer, based on a feedback loop of the process. This allows for a design process in which humans and robots engage in a dialogue, through a continuous exchange of questions and answers (Negroponte 1973).

In this dialogue, the human designers are responsible for setting the design parameters and constraints as well as being in charge of the broader design concept. The robotic agents on the other hand, being able to process complex geometries in a fast and accurate manner, are responsible for translating them into fabrication data. The process then unfolds until a satisfactory level of implementation has been achieved.

### *TERMES Project*

The *TERMES* project (Fig. 2) examines the capabilities of a new type of robotic fabrication system that is adjusted to the specific needs of a construction site. The research focuses on the fabrication of simple geometries utilizing a Robotic Swarm. The swarm consists of a number of small size autonomous robots that interact with each other as well as with the environment on a local basis. Each Robotic Swarm operates individually, and as a result, small-scale collective behavior emerges (Gadsby 2010).

The approach is inspired by biological clusters and follow simple rules (Napp & Klavins 2010). Furthermore, there is no collective audit principle to govern their behavior, which is determined locally through the interaction between the members of the swarm. This leads to the emergence of a collective intelligent behavior, independent from each individual robot (Werfel et al 2011).

The case of the *TERMES* project demonstrates certain advantages in the Robotic Swarm approach to fabrication. These include high reliability, reduction in the complexity level of the design and significantly lower costs per unit. Moreover, the utilization of swarms limits the possibility of a catastrophic failure or of significant deviation. It further guarantees the continuation of the construction process, even in the event that a significant number of the swarm members are out of commission. This distributed and open structure facilitates deployment of the swarm in all types of terrain. Furthermore, it ensures operational flexibility during the fabrication process since it allows for changes and revisions during operation, thus significantly reducing costs.

## FRAMEWORK OF DESIGN PLATFORM

Analysis of the state-of-the-art highlights a gap in communication between Design Standards and Swarm Robotic Fabrication Units. This leads to significant limitations in relation to the flexibility of the fabrication process and the complexity of the final product.

The research presented in the present paper aims to fill this gap through the development of a tool consisting of two key innovative elements: on one hand direct connection between Digital Design Environments and the Robotic Swarm, on the other hand development of a platform that allows for real-time management of fabrication analytics. These elements will facilitate the implementation of swarm robotic fabrication in architectural construction processes.

Incorporating the aforementioned elements, the presented tool aims to provide a bridge between Design Software and Robotic Software. This in turn will facilitate the further development of a framework for integrating robotic fabrication methods in the architectural design process.

The tools described in the previous sections have been implemented in the proposed framework. The resulting design methodology is comprised of four stages : (a) Scanning, (b) Data Analysis, (c) G-Code Generation and Construction, (d) Monitoring and Evaluation.

### *Scanning Stage*

The process begins with the Scanning Stage (Fig. 3). It involves the mapping of the selected area and the identification of the prevailing elements. This maps out the environment in which the Robotic Swarm will be deployed, and operate. The stage consists of two discrete steps: Geographical Mapping and Data Processing.

The Geographical Mapping step includes, two groups of actions: recording and data-collection. Specifically, during the recording action, all relevant data regarding the environment, such as visualization of ground materials, search for waypoints (where the Robotic Swarm will be deployed) and so forth, are recorded, filtered and stored. This is achieved through aerial reconnaissance via drones, as well as on-site high-resolution photographic survey. The resulting data is further processed through various software tools. Through the use of photo scanning software as well as three-dimensional CAD software, a first representation of the environment is created (Fig. 3).

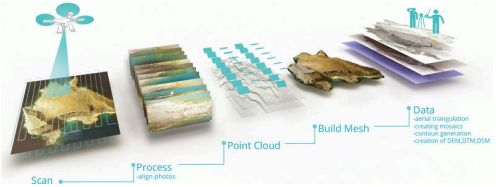
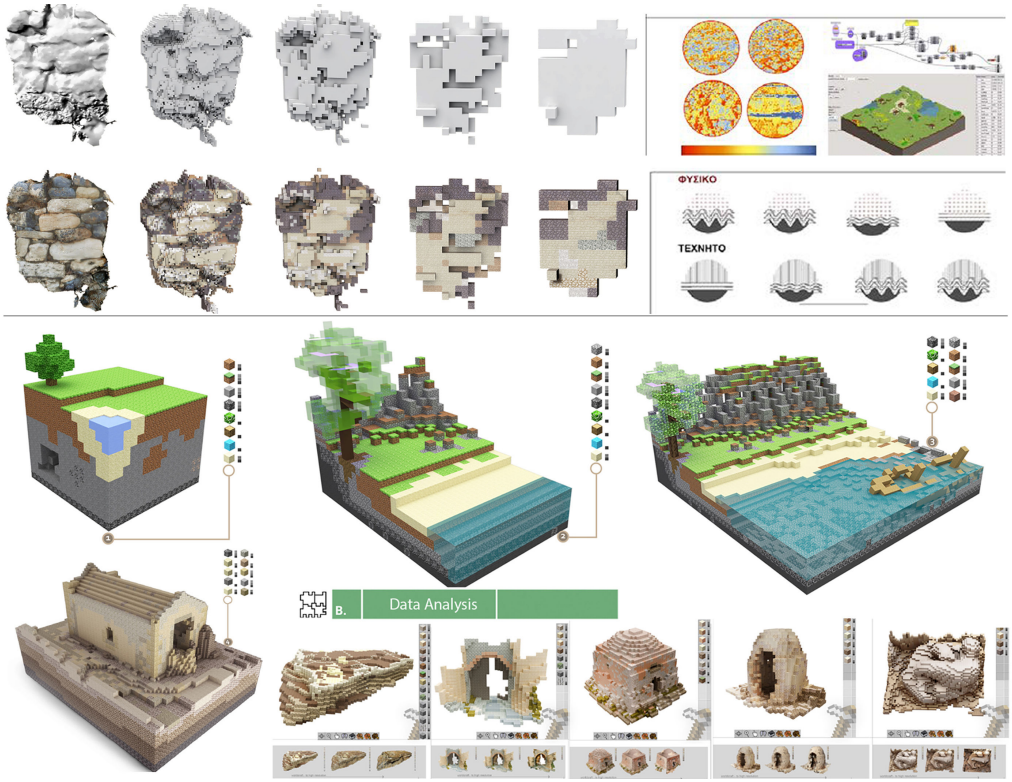



Figure 3
Stage 1 : Scanning Process. From point cloud to data (using existing area as a case study).

Based on this representation, Grasshopper 3D plugin for Rhinoceros is utilized in order to identify and classify the environment materials, in accordance with the recorded database. As a result, the process defines patterns to encode the different materials. In case of errors in the analysis via Grasshopper, the user can intervene using a virtual reality framework, based on the Oculus Headset and the Unreal Engine, in order to correct the model. Finally, the data is exported to formats that can be incorporated in design software platforms (Data Collection Actions). Additionally, during this step, classes and filters for organizing the data are identified and indexed data sets are created, which will facilitate the synthesis of the model of the "working surface".

The second step involves Data Processing (Fig. 4). During this step, the data collected through the Geographical Mapping phase is processed, through a vb-script in Grasshopper 3d, in order to create a three-dimensional model of the environment in question. At the same time, the collected data is categorized according to the filters and classes defined in the previous phase. This allows for a further analysis of the environment and creation of a database of the site properties. This database is then exported to Stage 2.

Figure 4
Stage 3: Data Analysis. Material to pixels - data (Bridging Minecraft with Grasshopper 3d)(using existing area as a case study).




### *Data Analysis*

Following the collection and classification of data in the Scanning Stage (Stage 1), the second stage, Data Analysis, focuses on information processing as well as optimization of the created three-dimensional environment. Key challenge in this stage is the processing and management of large volumes of data and the simultaneous reduction of required computing power. This is essential for limiting the complexity of the proposed platform, ensuring an efficient and user-friendly environment.

Utilizing the existing open world three-dimensional platform (Kamimura et al 2001) previously described (Minecraft) the proposed methodology is able to model and compile the geographical mapping of Stage 1 into structural blocks. Furthermore, each block is assigned with properties, based on the database imported from Stage 1.

This is achieved through the creation of a Grasshopper Definition that translates triangular surfaces (meshes) into three dimensional cubes. Following this translation, each block is inserted into the Minecraft plugin and is assigned with parameters drawn from the material database, utilizing the Minedit software. As a result, the diversity of the mapped environment is represented in the three-

dimensional model. Upon completion of the model, both topographical maps, as well as diagrams of material distribution, are available for the next stages (Fig.4)(Fig.5).

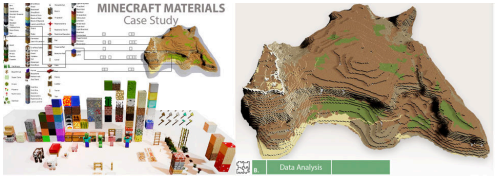



Figure 5
Stage 2 Data Processing. From pixel to data (using existing area as a case study).

### *G-Code Generation and Construction*

In this stage, the information collected and processed in previous stages is fed to the Robotic Swarm (Fig. 6). During this stage, the desired design is introduced into the platform and projected onto the three-dimensional model, allowing the extraction of G-Code in order to commence construction by the robotic swarm. This utilizes the database of topographic maps and material distribution diagrams created during stage 2. During the processing of the model, the user is provided with reports regarding the limitations and feasibility of the construction process, as the system calculates the collection points, properties and quantity of materials present in the site, as well as the available fabrication units.

Once the user decides on the final design solution, the process of encoding the structure for construction begins. Calculating the economy of material and work required, the system processes the design model. Based on the complexity of the form, it calculates the material resolution (high complexity equals high analysis, low complexity equals low analysis). Furthermore, the system checks the required material quantities in relation to the available collection points and their proximity, in order to achieve the optimal supply-demand flow during the construction process. Following the encoding process, the user has the option to alter the analysis as well as the design model itself.

When the construction process commences, the Robotic Swarm initially performs an environmental survey and sets construction constraints. Based on the data collected, the platform processes implementation scenarios in order to identify the optimal manufacturing solution. After the optimal solution has been identified, it is cross-checked with the parameters set by the designer. Upon completion of this verification process, the design code is created and downloaded to the Robotic Swarm.

The design code consists of four parts (Fig. 6): a) The creation of reference points on each cube, which are placed in a matrix and classified according to their characteristics, b) Connection of reference points, in order to create a toolpath, c) Distribution of the various construction tasks to the various members of the robotic swarm, based on the individual unit's characteristics and the complexity of the task, and d) Estimation of construction completion time, based on the average time required by each individual robotic agent to complete a specific task.

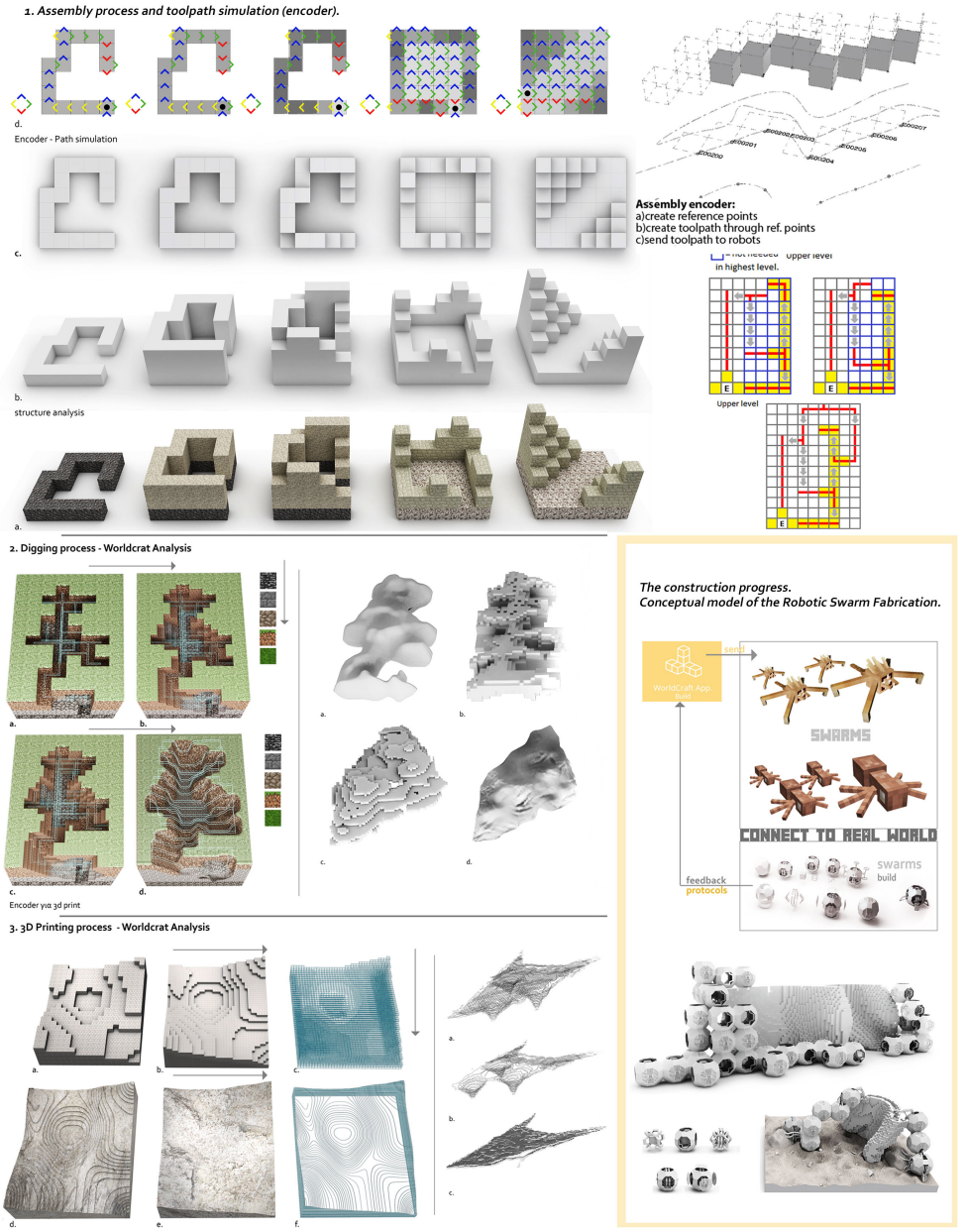
### *Monitoring and Evaluation*

With the creation of the G-Code complete, the robotic swarm follows a series of missions before commencing the construction. First, a reconnaissance of the area is performed, in order to create a detailed topographic map as well as waypoints and beacons. Second, a Central Support Unit is created, in order to collect and process the materials, as well as a network of Secondary Facilities in various Sectors of the site, that support and streamline local construction tasks. Finally, a hierarchy of the various construction tasks is defined, and they are assigned to individual robotic units based on the specific nature of the task and each unit's capabilities.

In parallel to the fabrication process carried out by the Robotic Swarm, the control platform is continuously fed with data from the Swarm's sensors. This allows for the collection of additional information regarding both the progress of the construction process as well as changes to the environment.

At all stages of the process, the designer is able to monitor and evaluate the construction progress (Fig. 6). Therefore, the design model can be updated

Figure 6
Stage 3:
(Top)Construction A. Assembly process and toolpath simulation (encoder).
(Down)Construction B, C. Digging and 3d printing process.



with new data which can then be fed to the Robotic Swarm in the form of new construction goals, creating a dynamic feedback loop that constantly evolves as the fabrication process unfolds

## ROBOTIC FABRICATION PLATFORM EXPERIMENTS

Following the previous description of the conceptual framework showcasing the proposed platform 's design methodology , preliminary research results regarding the development of the collaborative multi-agent Swarm Fabrication platforms will be presented. These involve two experiments regarding the development of the robotic fabrication swarm agents: Hexbug Swarm of Robots and Robotic Units based on Braitenberg vehicles. The research is based on a combination of tools, including Grasshopper 3D, Processing, Python, ReacTIVision, drones and small commercially available robots.

### *Hexbug Swarm*

The first experiment focuses on the investigation of swarm behavior and control. The robots are directly controlled through Grasshopper and their location is identified utilizing ReacTVision (Oungrinis et al 2015). The goal of this phase of the research is the investigation of the robots behavior in simple scenarios. These include transition to specific points, self-organization in order to navigate obstacles, collision detection, transportation of building materials and construction at designated location (Fig. 7). The agents are considered to have an exploration task, covering an unknown area as a cooperative acting robotic swarm.

The robotic agents are assigned with an exploration task, covering an unknown area as a cooperative acting Robotic Swarm. In the context of the presented experiment, small scale commercially available robots were used. Modifications were made to their controlling software and communication protocols. This is in-line with the stated goal of the research to minimize the cost of deploying a robotic swarm, by utilizing inexpensive agents in large numbers.

The robotic platforms utilized in the experiment are the following: (a) Arachnoid (fig.7) : 6 legs - 1 arm robot equipped with a robotic arm for use in 3d Printing and Excavation tasks, (B) Nano - Arachnoid : Robotic Platform utilized for Networking Tasks, and (C) Arachnoid Drone : Robotic Platform equipped with a scanner system utilized in Exploration and Coordination Operations Carrier: 12 legged Robotic Platform tasked with material Transportation and Relocation.

### *Robotic Units based on Braitenberg vehicles*

Reactive systems are comparatively new to the field of robots. They are based on the combination of sensors with a group of low level behavior programming, based on neuronics and cognitive psychology (French & Canamero 2005). The variety of ac-

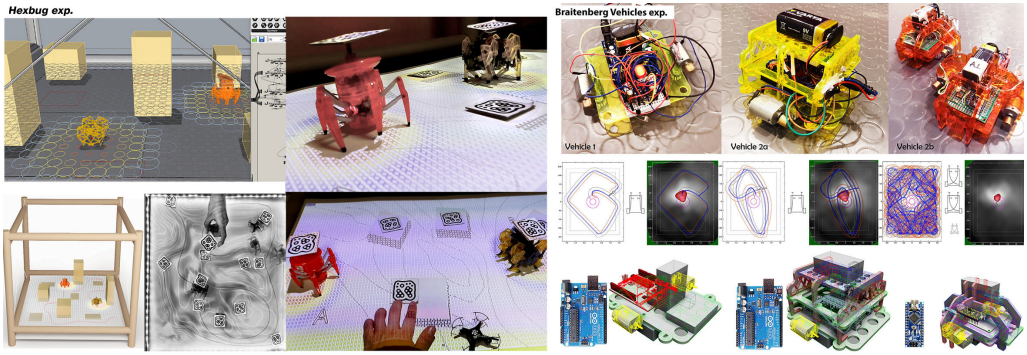



Figure 7
(Left) Hexbug Swarm Of Robots, Communication Platform. Digital and physical Model Simulation, Rhinoceros 3d & Grasshopper. (Right) Braitenberg vehicles, test models (ongoing experiments).

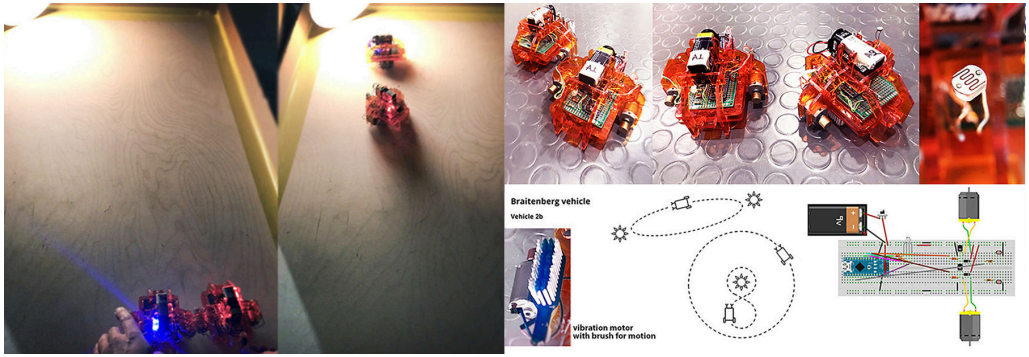



Figure 8
Braitenberg vehicles. Ongoing Experiment V1, single agent and V2b collaborative tasks.

tions stems from the interaction between different behaviours, the readings of the sensors and the environment. Reactive systems are suited to dynamic environments which are in constant flux, thus excluding the utilization of a static map.

The main characteristics of reactive systems can be described as follows: (a) Behaviors are essential parts of design. A behaviour in reactive systems is usually a combination of sensor and motor activity. The sensor-reading triggers the motor in order to move towards or away from the source (e.g. destination or obstacle). (b) General knowledge of the environment is avoided. The creation and maintenance of a detailed representation of an environment is a time-consuming and costly procedure, prone to errors. On the contrary, reactive systems do not store a representation of their surroundings, but react to stimuli from the environment. As stated previously, this is of value in unpredictable and dynamic environments. (c) Reactive systems are usually modelled on animal behaviour patterns. Frameworks from the fields of neuronics and cognitive sciences are used to model the behaviours necessary for the robot's interaction with the environment.

In the second experiment, Braitenberg Vehicles are utilized in order to understand the movement of plants and animals towards or away a source in a reactive manner (Braitenberg 1984). The type considered in the present paper are symmetrical assemblies, equipped with two frontal sensors, along with a stabilizing wheel as well as two rear wheels, connected to two independent motors (Fig. 7)(Fig. 8).

The vehicle is controlled through a system that connects the right sensor with the right wheel and the left sensor with the left wheel. When a sensor is triggered, the corresponding motor is activated, thus rotating the vehicle in the corresponding direction. The process is repeated until the vehicle reaches the source of the signal. An alternative system involves connecting opposite sensors and motors (right sensor with left motor and vice versa). In this case, the vehicle is guided away from the source of the signal (Fig. 8).

## CONCLUSIONS

The research work presented in this paper aims to explore issues arising from the difficulty of handling complex data produced from architectural design processes in the context of robotic fabrication.

This difficulty is due to the fact that contemporary architectural design contains embedded within it multiple layers of information, with plenty of abstractions. This information is varied in nature, ranging from geometric data, which is accurate, to material information, which is given as an abstraction/connotation. Due to this fact, the translation of this data to fabrication files and codes remains a daunting task.

The proposed platform aims to handle the conversion of design data to fabrication code, adjusting dynamically the resolution and the materials required. This is achieved through the parceling of the information into manageable sub-groups, that are in turn further analyzed, according to the application context, in order to provide a specific fabrication code for the Robotic Swarm for the distinct condition. This is made possible by two key features implemented in the proposed platform. Firstly, the combination of already existing technologies within a new framework of data analysis and data processing. As a result, the application is cost effective, since it embeds already developed technologies, on a different operational matrix. Secondly, the proposed framework is scalable and adaptable to a large variety of tasks. materialities and environments.

In conclusion, the proposed platform aims to create a new paradigm for integrating architectural design and robotic fabrication. This integration can lead to an evolution of the design process by facilitating a dialogue between designers and robots during the architectural process.

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# Integrating biophotovoltaic and cyber-physical technologies into a 3D printed wall

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*The research presented in this paper investigates the development of ``3D printed ceramic green wall'', a technological Nature Based Solution (NBS) aimed at regenerating urban areas by improving spatial quality and sustainability through clean and autonomous energy production. Building upon previous research, the challenge of this system is to adapt additive manufacturing processes of ceramic 3D printing with biophotovoltaic systems while simultaneously developing digital and cyber-physical frameworks to generate site and user responsive design and autonomous solutions that optimize system performance and energy generation. The paper explores the complex design negotiations between these drivers, focusing particularly on their performance optimization, and finally highlights the system potential as exemplified through a successful implementation of a 1:1 site responsive wall prototype.*

**Keywords:** *Nature based solutions, biophotovoltaic systems, additive manufacturing, responsive design, cyber-physical networks, augmented reality*

## TECHNOLOGICAL NATURE BASED SOLUTIONS

Nature Based Solutions (NBS) are systems that work with nature to address socio-environmental challenges, providing cities with solutions to address urban issues using a holistic approach. They are defined by the European Commission as "living solutions inspired by, continuously supported by and using nature, which are designed to address various societal challenges in a resource efficient and adaptable manner and to provide simultaneously economic, social, and environmental benefits" (Bauduceau et al. 2015). These innovative systems should take advantage of advanced digital manufacturing methods and technological developments to provide novel design protocols and possibilities for enhancing urban design, both in the quantity and quality of public space intervention. The 3D printed ceramic green wall falls under the framework of these Technological Nature Based Solutions and utilizes a multidisciplinary design approach, traversing technology with biology, to innovate the solution design, implementation process and responsiveness, and optimize system performance.

The 3D printed ceramic green wall relies on the conclusions of two precedent IAAC investigations which are of particular interest: FoodVoltaic and Digital Adobe. FoodVoltaics is a green wall system which explores how herbs might be used as a source of renewable energy through biophotovoltaic technology, which allows for the production of small

amounts of energy through the naturally occuring electrons generated due to photosynthesis. On the other hand, Digital Adobe demonstrates the potential of building full-size robotically 3D printed wall prototypes using clay materials, which can improve the sustainability of buildings by optimizing the qualities of the clays and can extend the possibility of developing complex geometries to house the organic matter and technical equipment and sensors. The challenge associated with the 3D printed ceramic green wall consists of adapting the manufacturing process of Digital Adobe to the needs of the FoodVoltaic system, while also integrating I2oT sensors and communication electronics connected to a cloud computing platform for data acquisition and analysis with the objective of optimising the processes of energy generation. As a green wall system, the 3D printed ceramic green wall can be applied strategically to help regenerate urban neglected areas by improving their spatial quality and sustainability through clean and autonomous energy production while simultaneously boosting the quality of the physical environment.

In contrast to traditional green walls, the 3D printed ceramic wall is a sophisticated system designed according to the elaborate relationship between physical processes and the cyber systems they govern, and vice versa (Figure 1). The realization of this cyber-physical system relies on several drivers: on biophotovoltaic technologies for energy generation and collection, on robotic additive manufacturing for novel materials and mass customization, on a responsive design platform to allow for design adaptations to site-specific conditions, and finally on a platform of sensors, cloud computing and machine learning softwares, and immersive visualizations systems to study system behaviour and provide predictive and corrective measures for optimizing system performance. The complex negotiations between these design drivers will be further explored.

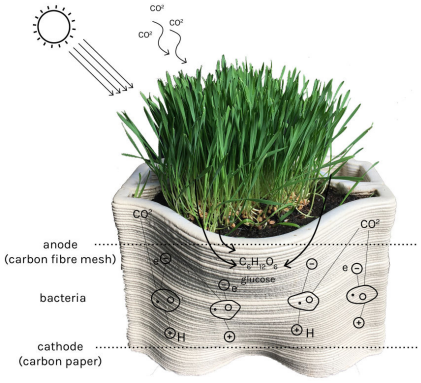
Figure 1
3D printed ceramic green wall outcome as a sophisticated system-driven solution

## BIOPHOTOVOLTAIC SYSTEMS: PLANTS AND ELECTRICITY

In order to generate electrical energy, the 3D printed ceramic green wall relies on a biophotovoltaic system (PBV) that exploits the natural process of photosynthesis. The plants use energy from light to consume carbon dioxide and water from the environment and convert it into organic compounds, which are then released back into the soil containing symbiotic bacteria. This bacteria feeds and breaks down the compounds, releasing byproducts that include electrons. By providing an electrode within the system for the microorganisms, the resulting electrons can be collected as electricity.

The energy collection system developed was based on the previous research carried out at Cambridge (Wey et al 2015) and consists of an anode (carbon fibre mesh) and a cathode (carbon paper). The carbon fiber mesh was embedded into the soil substrate for root growth contact and the carbon paper was positioned strategically onto an opening in the bottom of the container to provide oxygen to the root system through this semi-permeable barrier (Figure 2).

Figure 2
Diagram of biophotovoltaic system components and processes




This system was implemented and tested over a 6-month period using standard plastic containers along with sensors to monitor plant growth over time to understand the logics behind a healthy system. The sensors fitted analyze both the internal conditions of each pot (temperature, soil moisture, pH, electrical conductivity) and the external conditions of the surrounding environment (air temperature, humidity, lighting, NO2, CO). The following conclusions were generated for the system to thrive and generate maximum electricity:

- Higher water saturation yields higher electrons due to the additional water in the medium promoting electrolysis within the soil.
- A positive correlation exists between the quantity of electrons generated and time passed.
- The larger the root growth, the more productive the system is, and therefore containers with larger soil volumes generated the most electrons.
- The bacteria in the soil is aerobic, requiring openings in the base that allows exposure to oxygen in addition to excess water drainage.
- The anode and cathode need to be distanced, otherwise the system short-circuits upon contact and energy collection fails.
- The process of energy generation is interrupted by the evaporation or freezing of water from the soil.
- Each system relies on the healthy growth of the plant and every plant species requires different conditions of light, water and root growth capacity to meet those requirements.

This final deduction highlighted the importance of plant selection and led to further investigation into specific plant typologies and the subsequent correlation between growth requirements and variabilities within the planter morphology. Because the prototype was to be erected within Barcelona, two categories of plant species were considered: Native edible plants suited for Mediterrainean climates that can be applied to outdoor settings, and tropical low-maintenance plants for indoor applications. Plants of each category were selected and their performance analyzed as a function of light, water, and root growth mass comparatively over different planter morphologies. General observations recorded suggested a relationship between the ratio of the amount of plant tissues above ground to the amount of those below ground and the supporting soil volume. Plants with smaller above ground biomass fared better in shallow planters with smaller soil volumes thanks to their size proportional root structure systems. Similarly, plants with larger above ground biomass fared better in larger planters that could support a higher soil volume. Additionally, the surface area calculation of the planter's topsoil had a positive correlation to the moisture content within the planter; an increase in top surface area resulted in an increase in water evaporation from the soil.

## ADDITIVE MANUFACTURING: CERAMICS AND DESIGN

Robotic additive manufacturing technologies offer a new flexible methodology for manufacturing green wall systems in part due to novel material possibilities and the ability to mass customize complex geometrical forms The first phase of the investigation focused on identifying a locally sourced clay body suitable for printability and potential application within the 3D Printed Ceramic Wall. Studies focused specifically

on stoneware, known for its robust working properties and extremely low water absorbency levels when compared to other ceramics, which is crucial for preventing damage from extreme outdoor weather conditions and the internal high water content required for the biophotovoltaic system. Stoneware can be glazed to achieve similar strengths to porcelain, is significantly cheaper in costs, and has a lower shrinkage rate, a property fundamental to controlling material behaviour at every step of the formation process, from fabrication to firing.

Ceramics undergo two stages of uncontrolled shrinkage, once during the drying process and again during the firing process. As water evaporates from the clay body, the resultant particle packing shrinks the entire matrix, highlighting the importance of the water content and clay particle size on shrinkage. Water content also plays a critical factor within the additive manufacturing process in achieving the required material consistency and malleability for optimal extrusion. Material studies were conducted to understand the critical relationship between the water percentage of a clay body on both clay behaviour and its resulting influence on performance post-firing. Five varieties of stoneware were selected and tested at various water content levels, and compared for printability, viscosity, total shrinkage, material strength, and water absorption. The resultant data indicated that the PRAM clay, manufactured by SIO-2®, with 22% added water outperformed in reducing the percent of change in material behaviours and was therefore selected for its optimal performance in both wet and fired state (Figure 3).

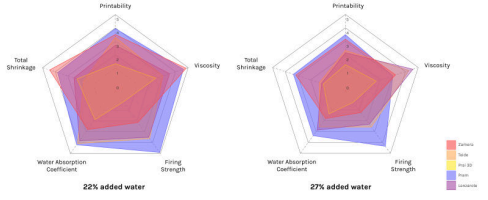



Figure 3
Comparison of documented changes in material performance as a result of varying water content in clay bodies

The second phase focused on investigating the material and structural limitations of 3D printing based on previous work developed at IAAC along with testing to extract a set of patterns and rules to define the geometry. Initial printing experiments helped deduct the following guidelines for successful structures:

- Any geometry needs to be sliced into layers of continuous printing paths for production optimization.
- Walls with double curvature achieve greater stiffness and resistance to stress deformation than vertically extruded straight lines, measured by its resistance to buckling.
- A volumetric structure can reach a maximum stable height of up to 60cm by increasing the number of vertices within the printing path.
- While infill can greatly improve structural stability, it also significantly increases the material required and therefore the weight of the final object.
- For stability, it is important that the center of gravity of the body remains within the boundaries of the footprint of the geometry.
- Any geometry can exhibit a maximum overhang angle of 30°, but with appropriate and adequate infill, this angle can be increased up to 40°.
- Rotation and torsion coupled with a shift in the center of gravity of the top layer with respect to the bottom layer may result in structural instability.
- Any structure should be designed considering a total material shrinkage of 11%, resulting in a dimensional tolerance within +/- 0.5-1.5mm assuming the drying temperature and humidity levels are controlled.

Prototype investigations were conducted to further extend the design possibilities and geometrical complexities achievable with additive manufacturing towards pot functionality. Several prototype designs of horizontal and vertical extensile iterations were analyzed for their potential for parametric variability as required of the pot morphology to support the growth requirements of various plant species. In designing the pot module, it became critical to un-

derstand the part-to-whole relation to drive further system development. Initial starting design investigations were oriented towards creating a seamless wall, whereby the edge boundaries between pots joined to minimize the separation between them. Ultimately, a component-based wall system proved to be the ideal condition as a result of the warping that occurs from the uncontrollable shrinkage of clay during the drying and firing process, compromising any attempt at creating seamless joineries. In order to improve the surface quality of the pots, explorations of textural applications were explored and imposed to force a controlled patterning system. The multipurpose surface texture of the pot not only serves a visual purpose, but it also increases surface area to provide more humidity control and further stabilizes the structure of the pot due to the increase in the number of vertices that help counter the buildup of material loads. Exterior glaze finishings were applied to program necessary flora conditions related to light amplification through increased reflections.

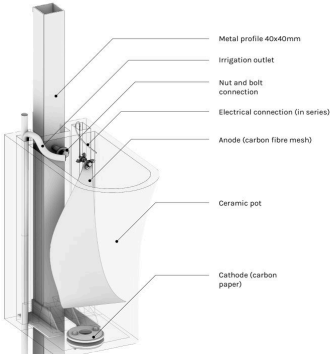



Figure 4
Unit axonometric of components and structural detailing

In addition to housing organic matter and biophotovoltaic components, the pot design integrates a standardized structural system, adaptable to any height, that allows for easy installation onto the secondary support structure and ease of maintenance or replacement. This bottom detailing allows the pot to safely slot onto two L-brackets and is secured from the top by a nut-and bolt system to prevent rotational moment. A secondary nut-and bolt system secures the carbon fibre mesh in place, preventing a system short circuit, and providing an outlet for the modules to be connected in series and in parallel for energy collection (Figure 4).

## INTEGRATION IN DIGITAL INTERFACES: RESPONSIVE DESIGN

Computational design softwares, specifically Rhino and Grasshopper plug-ins, were implemented for design modeling and optimization of solutions as well as facilitating the development of a common design platform that allows for adjustments based on defined parametric inputs. This algorithmic script influences the system design on both the individual pot level and the overall global system design according to site-specific and regional-specific inputs, resulting in an innately responsive design.

The script allows for the topological variability of each pot through two parameters vital to the success of any plant species growth and energy generation: height and opening angle. An increase in the height of the pot allows for greater soil capacity and can support plants with larger roots, while a decrease in height yields less soil capacity and best support plants with smaller root systems. Similarly, the opening angle of the planter can be modified to control the soil moisture levels by increasing or decreasing the surface area exposed to water evaporation from the soil and are defined by a plant's ideal water and humidity conditions.

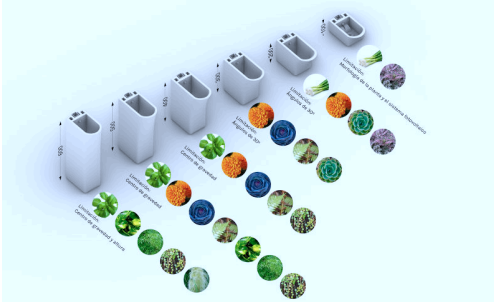


Figure 5
Catalogue of pot height and angle limitations with respective flora possibilities

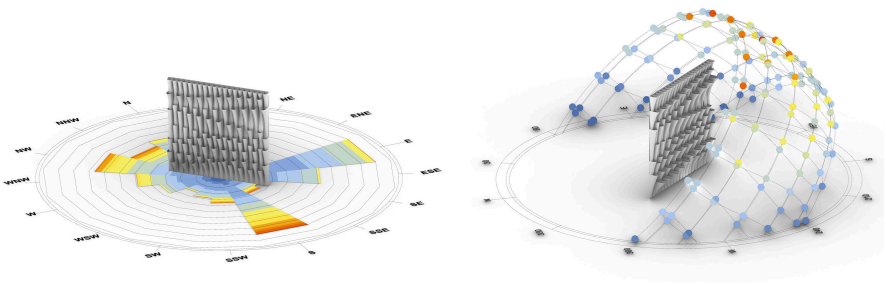


Figure 6
Generated wall design for Barcelona driven by local environmental inputs including solar path and wind

| Local (Site-specific inputs) | Global (Regional-specific inputs) |
|---|---|
| Local flora requirements | Temperature |
| Solar Path | Humidity |
| Wind | Rain |
| User preferences | |

Table 1
The responsive inputs considered by the algorithm script

Globally, the system parameters consider specific local site conditions, as well as specific regional and global environmental conditions, and distributes the most suited plant variety and subsequent pot morphology accordingly (Table 1).

While plants need light for photosynthesis, a process critical for biophotovoltaics, not all plants require the same light nor is all light the same. Understanding the sun and light intake requirements is vital to determining the optimal opening angle and distribution of the modules. The solar path, altitude and azimuth angle help determine shadow regions and appropriate pot opening angles. Wind equally is important for plants as it helps them grow sturdy yet strong or cold winds can damage or kill plants by drying out the soil moisture levels. Plants that are densely branched to the ground, such as basil, marigolds, and ferns, can act as windbreaks by strategically placing them to protect vulnerable plants highlighting the importance of plant selection for extreme environments. Similarly extreme heat, humidity and rain all have significant effects on the soil moisture content levels, a factor that can be very detrimental to both the biophotovoltaic system and plant health, yet can be mitigated through appropriate plant selection and controlled irrigation (Figure 5).

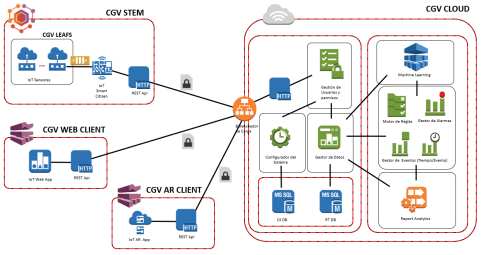
The algorithm also supports design influences from external actors within the design process. The flexibility of this system can facilitate the negotiations of these open-ended parameters between citizens and their city governments, empowering communities. Due to their subjective nature, these participatory design parameters rely heavily on preferences, accommodating varying degrees of user or client customization.

Figure 7
Potential system application in an urban public space context.

## INTEGRATION IN PHYSICAL INTERFACES: CYBER-PHYSICAL SYSTEMS

The cyber-physical platform associated with 3D printed ceramic green wall provides real-time information on the energy generation process through its expert analysis of data and use of immersive visualization tools, ensuring the sustainability and productivity of the wall. The architecture of this platform comprises the following technological elements: Green Leafs; Green Stems; Green Platforms; and Green Client.

Figure 8
Cyber-physical system architecture




Each independent module found in the wall system intended to house plants and fully functional biophotovoltaic systems is referred to as a Green Leaf. As previously stated, this biophotovoltaic system consists of an anode made of carbon mesh fibers to help attract electrons and a cathode made of carbon paper, which attract protons from the anodic biological material. Each Green Leaf is fitted with a water irrigation outlet and a number of I2oT sensors for monitorization of the energy processes based on plant photosynthesis. The sensors embedded within the Green Leafs analyze environmental and plant conditions. The different sensors (Green Leafs) are connected to a Smart Citizen Kit v2.0 SCK, which is an Arduino-based open software platform acting as a central controller (Green Stem) and is responsible for collecting real-time data from the sensors, pre-processing it and sending it to the cloud computing software system (Figure 6).

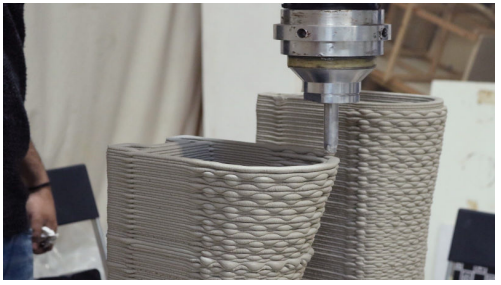
Figure 9
Voltage energy readings for one of the Green Leafs and the substructure of the supporting structural, irrigation and electrical systems

The Green Platform, or the cloud computing infrastructure, integrates both the hardware elements required for the cloud infrastructure (Green Cloud) and the software elements (Green ML Brain) required for analysis, archiving, optimization, and decision making. In addition to storage and management of energy and real-time data, the cloud infrastructure also allows for the analysis of data obtained through automated machine learning algorithms to optimize production processes and facilitate predictive maintenance of the different distributed Green Leafs.

The final element of this cyber-physical architecture is the visualization elements that operate through either platform-independent applications with valid internet connectivity (Green UI Client) or applications based on augmented reality techniques for devices with built-in cameras (Green AR Client). These immersive visualization systems offer a more informative understanding of the data obtained and ultimately a more effective overall user experience.

## PROTOTYPE PRODUCTION AND ANALYSIS

Figure 10
Production of the 3D printing ceramic pots



To test the viability of the overall wall system, a prototype was designed, and developed within a real-world environment with the objective of carrying out the complete integration and validation of the digital and physical platforms to monitor effectiveness and optimize the energy production system. The selected study site was the city of Barcelona and the prototype was evaluated in two locations, one within the IAAC laboratories, and the other was exhibited and demonstrated to the public during an international

construction fair. The relevant global and local climatic conditions were input into the algorithmic software, and a 1.2x1.2m sectional of the resulting parametric wall generated was extracted and selected for mass fabrication. In total, 21 modules were 3D printed, dried, fired, and glazed (Figure 8). The morphology of these pots ranged from 200 to 500mm in height with a maximum cantilever angle of 35.0°. The resulting outcome of this analysis best supported sturdy and low maintenance plant varieties, including fern, pothos, asparagus, echeveria, hypoestes, and rosario.

The pots were assembled onto a self-standing metal structural system developed using 40x40mm metal profiles to support the weight of the system and to integrate a cavity between the pots to store the automated irrigation system components: a 36L water tank, a water filter, and a pump. Once all the modules were installed and connected, the electrical wires were connected to the Smart Citizen kit to monitor the health of two plants through specific sensors. The hardware was also connected to an ipad screen that informed the public about the general status of the system, as well as an AR marker that allowed the user to install a free application to download and visualize the system health and productivity data themselves. This automated irrigation system is initialized when soil moisture sensors detect low levels, activating the pump to distribute water through a series of plastic tubes fed up through the metal profiles with outlets distributing water for each pot. The fair lasted 4 days, after which it was dismantled and transported back to its origin (Figure 9).

The hardware and software systems integrated in this prototype were successfully installed and worked well (Figure 10 & 11). The system was equipped with the sensors of a complete SmartCitizen kit together with other cheaper sensors using the KNX protocol. These sensors were integrated in two pots to correlate the data between the two and provide a good impression of the system status. The AR application was also successfully tested and provided users with the ability to scan the AR marker and go to the application to download and understand the data collected by the sensors. The automatic irrigation system was also installed and operated successfully.

Figure 11
Final set-up and assembly of the 3D print ceramic green wall, including the cyber-physical platforms

First feedback from the construction fair was highly promising, as visitors expressed their interest and appreciation for the greenery and aesthetics of the system. The positive reception received suggested a similar marked improvement on urban ecosystems thanks to the introduction of plants. One of the main issues with any green wall is its maintenance, however, the monitoring platform of the 3D printed ceramic green wall gives the system the ability to provide its own expert care for the plants with minimal and targeted external intervention if necessary. This cyber-physical platform, along with strategic design solutions integrated within the modules to avoid evaporation, help minimize the water consumption required by the system and maximizes the energy production.

Figure 12
The SmartCitizen kit providing real-time information on the health of the plants and energy productivity

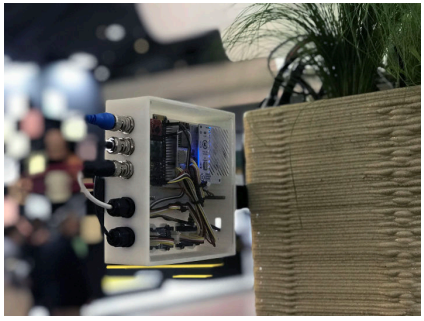


Figure 13
An augmented reality (AR) phone application allows users to visualize overall system health and to interact with each plant using real-time sensor data

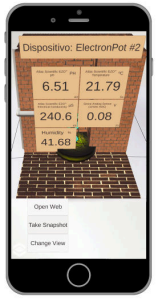



Figure 15

## CONCLUSIONS

The 3D printed ceramic green wall system featured in this paper has proven itself successful as demonstrated by the 1:1 prototype, paving the way toward its implementation in real world applications with a number of possibilities for further development. Significant improvements could help further simplify the assembly and installation process of the pots through either plug-in-play methodologies that simplify the connections between anode and cathode, or by exploring and integrating conductive materials into the additive manufacturing process to embed conductive performance within the material behaviour of the stoneware. Further research needs to be conducted to expand the repository of plant varieties available for applications within environments that fall outside of Barcelona's climatic conditions, while also considering the possibility of adapting the system for urban agriculture in which the local products may be cultivated. Another design opportunity lies in embedding an augmented reality code marker into the textures of the modules, so that each texture may transform into uniquely identifiable markers that provide specific data to that module's energy readings and plant health.

Lastly, the digital fabrication of 3D printed ceramic green wall has only been tested at a maximum scale of the 1:1 prototype, and its immersion and relevance within urban spaces depends on the implementation of on-site full scale prototypes, in the formulation of a wider and deeper integration between additive manufacturing, responsive design, energy generation and collection, and embedded sensors. With each iteration, the productivity and application of this novel cyber-physical system improves and further solidifies the framework for a larger set of alternative plants, designs, materials, and processes yet to be explored.

## FUTURE PERSPECTIVES

The 3D printed ceramic green wall is part of the Urbinat Project Nature Based Solutions Catalogue. The solutions in this catalogue are to be co-selected by Nantes, Porto and Sofia citizens for implementation in deprived areas of their cities. The Catalogue Solutions will be co-selected in October 2020 and co-implemented in 2021. Urbinat Project focuses on the development of co-creation processes to stimulate neglected areas Urban Regeneration.

URBiNAT

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Figure 14
Data sensor readings of the prototype validation exhibiting marked improvements after March 12, a day when a system redesign was initiated.

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# D2.T8.S2. THE COGNITIVE CITY (AI)

# Urban Emotion

## *The interrogation of social media and its implications within urban context*

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*This paper presents social media as an analytical tool, helping to transform public policy-making, alongside urban needs by dissecting and evaluating human perception. Using emotion analysis on data gathered from a social media platform, experiments are developed to bring new value to architectural and civic narratives. Emotions from texts collected within social media platforms are extracted and mapped alongside tagged locations to gain a greater understanding of how public spaces are utilized. This project develops a new analytical layer within our built environment, working alongside the urban fabric, mechanical systems, and digital infrastructure. It is offered as an interactive tool for policymakers and designers to glean feedback, creating an informed conversation between citizens and decision-makers. Whereas social media platforms such as Twitter and Yelp have been referenced in past academic contexts, this project moves further by producing quantified emotions, painting a differentiated result from what purely semantic data could deliver.*

**Keywords:** *Social Media, Mapping, Natural Language Processing*

## INTRODUCTION

Big data has the potential to hugely impact the way urban scale decision making is rationalized in the context of urban engagement and interaction with our built environment. Layers of digital information allow cities to explore complex and dynamic aspects, especially when feedback loops are incorporated (Rabari and Storper, 2015). The conversation between digital sensing and processing bears the potential of affecting various aspects of the urban environment, and improving the economic, social, and environmental sustainability of the cities that people inhabit.

In recent years, architectural building projects have more commonly adopted the process of performing post-occupancy evaluations in order to quantify and compare expectations versus realized results. When considering human-centric qualities such as perception or behavior, however, this is not nearly as explicitly quantifiable or straightforward to evaluate. Therefore, this research focused on transformation from qualitative data to evaluation metrics by analyzing texts directly posted from users. Using Natural Language Processing (NLP), this research extracted types of emotions with corresponding intensity and mapped them on an interactive map based

on the geographical information users included. It enabled users not only to understand general perceptions of public spaces and their utilization but also to get individual comments about them.

## PREVIOUS WORK

Previous research has explored the potential of social media data in relation to urban contexts, identifying their application in interpreting urban environments, alongside issues of subjectivity quantification (Honig and Macdowall, 2017; Pfeffer et al., 2018; Thömmes and Hübner, 2018).

Chen, Nagakura, and Larson (2016) used API's (Application Programming Interfaces) available from Crunchbase, Yelp, Flickr, and Twitter to help identify what quantitative factors contribute to growing innovation hubs within the cities of Boston and Cambridge. Flickr and Twitter were used to identify activity and location over a time stamped and geolocated data set, whereas Crunchbase was used to map existing innovation hubs and startups for each particular business. Yelp then helped to map the density and categories of amenities, thus building a clearer picture of what characteristics contributed to the existence and growth of these innovation hubs. While this project made use of accessible API's for mapping trends geographically related to innovation hubs, it did not focus on the user-contributed content, losing the potential to further rationalize place-making based upon emotive input.

Rossi, Boscaro, and Torsello (2018) focused on the Instagram platform to build a tourism-centric and image-based analysis of Venice through mapping. They built an image classification framework using geotagged photos to classify their dataset within the scope of Lagoon, Townscape, Art, Folklore, Food, or Other. After comparing these classified photos to density and distribution of geolocations, they were able to create a tourism heatmap, which reflected how tourism was consumed and where. This project relied on using machine learning to classify images from Instagram posts and map activity through the newly discovered categories, while intentionally leaving the textual content out of the research scope.

More recently, Jang and Kim (2019) illustrated the usefulness of hashtags from Instagram to extract identity-related meanings in constructing an understanding of urban identity in four historically similar but culturally different cities in the Seoul

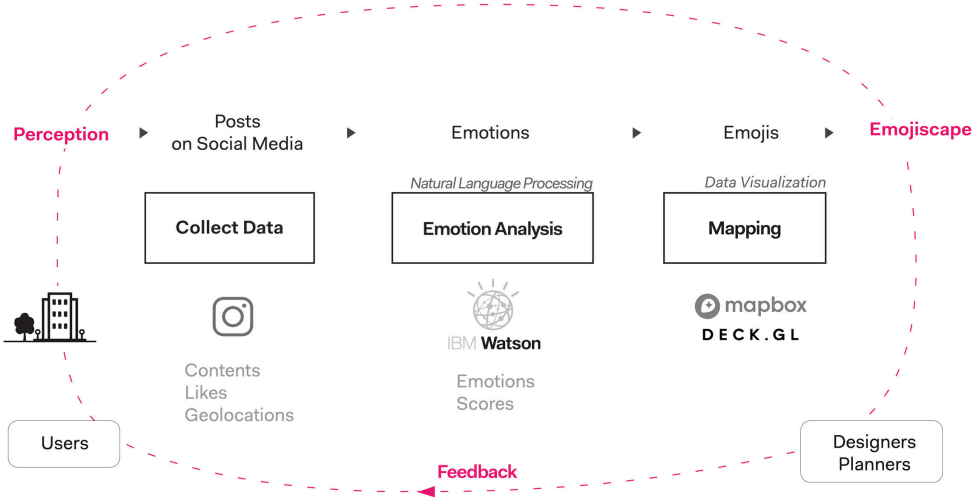



Figure 1
Process diagram showing how data collection translated to visualization and an emotive-data based feedback loop.

metropolitan area. The paper discusses how to quantify "subjective classifications" such as place identity and how crowd-sourced data available through social media and similar platforms can enable more accurate mapping exercises within urban environments rather than relying on historically prominent surveying, interviewing, and cognitive mapping. This project brought to light one of many valuable applications of textual content from Instagram data, though sought to investigate identity rather than emotive qualities.

## METHODS

### *Data Collection*

This project required a social media dataset for the quantification of emotions. Numerous resources were reviewed within available API's, along with third party services, which helped to gather and compile data points; social media posts with text-based descriptions were critical in this sense. The Twitter and Instagram API's were explored to determine whether educational access was possible to attain. In the case of Twitter data, the API was available for use, though geotagged tweets (a type of media with location added in) were infrequently found. Furthermore, the smallest location unit was neighborhood, which made granular analysis difficult. Alternatively, it was feasible to use a free web-based service called IFTTT (If This Then That) to scrape posts uploaded within a certain range of locations. However, in compiling a list of 2,000 tweets specific to this project's case study, it was concluded that the location data was not rigorous or plentiful enough for the sake of this research. Instagram presented a much more promising diversity of data, in that users were opting in to tagging their photos with specific locations of public and private places. Despite not all posts being geotagged, the proportion was considerably higher than Twitter, while also increasing location accuracy due to users highlighting the exact place a photo was taken. Through the use of Picodash, a third-party service for scraping Instagram's API, a CSV file with categorized data types was able to be obtained.

**Instagram, Picodash and Instaloadgram.** Instagram data has traditionally been a useful tool for researchers in many fields. However, recent issues with data privacy led to the platform shutting down most of their basic API services (Gummadi 2018) and moving to a business-only subscription model. As a result, a third-party service was necessary for this research.

Picodash is a search engine for Instagram, which is a paid, web-based service (Jang and Kim, 2019). The search engine allows exporting data from Instagram such as tagged geolocation, comments, hashtags, date/time stamp, and likes count. This information also includes emojis and exports as a CSV file, which is categorized by data type. An alternative service was Instaloadgram, which is a similar service based in Ukraine, targeted at social media marketers. It offers an export tool (similar to what was used for this research), hashtag generator, and comprehensive Instagram downloader, enabling customers to download photos, video, stories, highlights, etc. with targeted specificity. This research project worked with data from Picodash, as a result of lower cost, more customization possibilities, past history of use with other academic institutions, and higher levels of certainty as compared to Instaloadgram.

**Data Criteria.** This research chose to look at social media posts specific to the city of Boston. To gather such data, it was crucial to analyze how Instagram users interacted with the platform and how they chose city-specific locations. The hashtag "#boston" had over 20 million posts and thus provided a sufficiently large dataset to begin dissecting more finely. After understanding constraints in cost and specificity, 10,000 posts were purchased from the third-party service, which fit these specific criteria:

Table 1
Example of data found within CSV file. Each Instagram post is broken down by row.

| Index | Date | Caption | Comments_ | Likes_count | Location_name | Lat | Lng |
|---|---|---|---|---|---|---|---|
| 0 | 12/11/19 23:03 | holly n jolly times | 0 | 2 | Faneuil Hall Marketplace | 42.36015201 | -71.05528539 |
| 1 | 12/11/19 22:50 | Boston doing their part to include everyone in their | 1 | 11 | Faneuil Hall Marketplace | 42.36015201 | -71.05528539 |
| 2 | 12/11/19 22:49 | Snowcapped statues at Fanueil Hall on the way intc | 0 | 5 | Faneuil Hall Marketplace | 42.36015201 | -71.05528539 |
| 3 | 12/11/19 21:42 | #faneuilhall #faneuilhallmarketplace #christmasinbc | 0 | 1 | Faneuil Hall Marketplace | 42.36015201 | -71.05528539 |
| 4 | 12/11/19 21:08 | These holiday lights will never get old 🤓🎄 #tisthes | 0 | 15 | Faneuil Hall Marketplace | 42.36015201 | -71.05528539 |

*1.* Posts contained a geotagged location. *2.* Data were derived from 1000 most posted about locations in order to limit the scope to places that had larger numbers of posts for the analysis. *3.* The search filtered out the posts with the locations "Boston, Massachusetts," "Cambridge," "South Boston," and "East Boston" due to the broad nature of these locations. *4.* All posts were geotagged within a 2-mile radius of coordinate 42.361139, -71.058254, the centermost part of Boston, where Boston City Hall is located.

These criteria were intended to help specify posts that would be most useful and specific for our research, while still offering a breadth of location-related activity within the city. The resulting CSV file includes index, date, caption, comments_count, likes_count, location_name, latitude, and longitude columns (see table 1).

### *Emotion Analysis*

Posts without comments in a text format were removed, and 7,818 posts were available for analysis after this process. The emotion and score of each post was extracted from its content, using IBM Watson Tone Analyzer API (Ntshangase, 2018). Originally built to analyze and enhance the quality of customer support conversation, it uses Natural Language Processing (NLP) to detect emotional and language tones in written text. Tone Analyzer returns detected tone among seven different emotion categories–joy, sadness, anger, confidence, analytical, tentative, and fear–, with a confidence score in a 0 to 1 scale reflecting how strongly the tone analyzer interpreted each category. Posts were parsed using the Tone Analyzer, results were embedded into the post, and then converted into GeoJSON format.


```
{
    "geometry": {
      "type": "Point",
      "coordinates": [-71.06001,
       ↪ 42.35802]
    },
    "type": "Feature",
    "properties": {
      "index": 2835,
      "score": 0.857299,
      "tone": "joy",
      "caption": "There was a choir
       ↪ practicing when we walked in
       ↪ and the sound was beautiful.
       ↪ We got to sit in a booth for
       ↪ a bit and really listen and
       ↪ enjoy the moment. Such a
       ↪ beautifully up-kept historic
       ↪ church. Would recommend.",
      "date": "12/10/19 13:48",
      "comments_count": 0.0,
      "location_name": "King's Chapel",
      "lat": 42.35802,
      "lng": -71.06001,
      "likes_count": 16
    }
  }
```

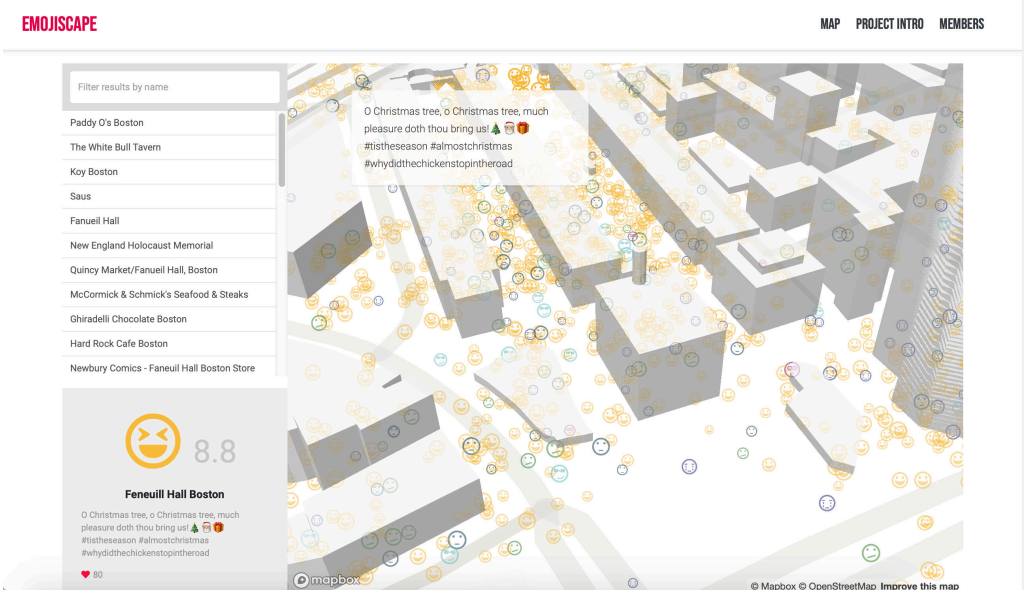

### *Data Visualization*

The main contribution of this research is the geolocated data mapping visualization, in order to help decision-makers and designers easily understand how public spaces were utilized and perceived by users. For this purpose, two projects were developed as part of this research: EmojiScape and TrendScape. The former was built to showcase emotion analysis, providing a qualitative representation of the inhabitants' perception of the urban fabric. The latter was designed to provide a different perspective on the same idea, focusing specifically on the temporal dimension of these emotions and the understanding of their evolving quality. Due to the divergence in goals, two different mapping platforms were used: Mapbox (Cadenas, 2014) and Kepler.gl (He, 2018) respectively.

Figure 3
Emoji key for emotions based on IBM Watson Tone Analyser.

In EmojiScape, the emotions were converted to simple emojis for visualization, and each emoji's size represented its score (see figure 3). Additionally, the original content was available when hovering on the emojis. It also highlighted emojis posted from the

Figure 2
The emotion analysis map, EmojiScape, shown with interactive emoji's and location-specific emotive readout as users traverse the city to different landmarks.



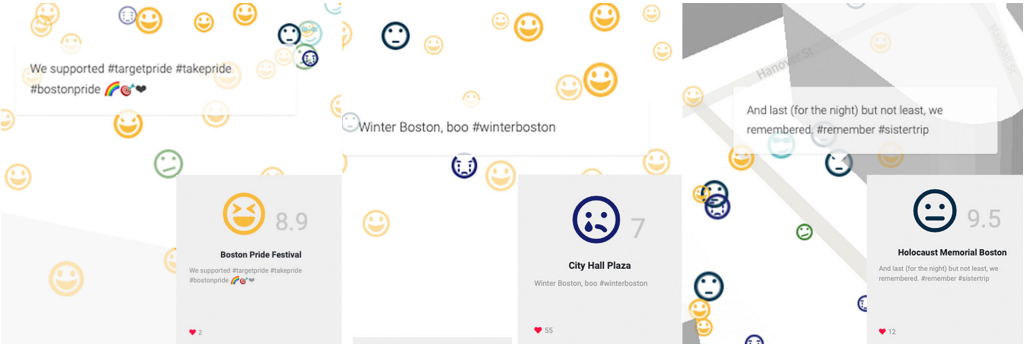

same location as well. In the left section, the search function enabled users to easily find the location by names. By default, it provided a list of places which the map was displaying at a particular moment (see figure 2).

In TrendScape, trends across temporal ranges could be highlighted, as well as activities related to time of the day. Data was represented on multiple layers on the map and with time filters. These functions made it convenient for decision-makers to compare the trends of spatial changes over date and time as well as over different public events (see figure 5).

## RESULTS

For the final outcome, two different mapping results were generated in the forms of EmojiScape and

Figure 4
Three examples of emotive readouts based on prominent locations. Note the idea of joy of a post from the Boston Pride festival or analytical nature at the Holocaust Memorial in Boston.



TrendScape.

EmojiScape was a visually-focused interactive map, through emphasized emotive responses and spatial landmarks rather than highlighting trends over time. The tool included a legend of places and events spanning from Boston's Pride Festival to Big Apple Circus. Upon engaging a location or region, users were presented with posts through an Emoji and score, along with the name of the event or place and caption of the post. The emojis directly correlated with Watson's Tone Analyzer's categorization. As an example, a happy emoji was associated with joy. A score of 8.9 out of 10 would mean that this was a very joyful post (see figure 4).

EmojiScape's tool had a powerful response among users. The tool very quickly provided a visual understanding of urban mood and emotion based on place. Numerous users noticed the striking presence

Figure 5
TrendScape trend study, showcasing a changing visualization of activity during differing blocks of hours during the day.

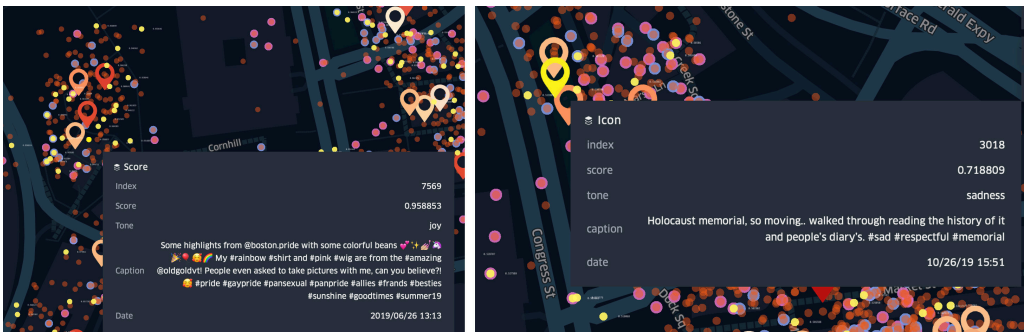



Figure 6
Posts from Boston Pride Festival (left) and Holocaust Memorial Site (right) from TrendScape map.

of sadness at the Holocaust Memorial site and anger at Boston City Hall, due to the dissatisfaction users had with some government initiatives and with the building's brutalist architecture.

Within TrendScape, users were able to select a day and track activity within the city, comparing daytime from nighttime and how density of posts or activity hubs transformed through time (see figure 6). As an example, post activity diminished significantly between the hours of 1:00 am and 7:00 am in downtown Boston. In terms of dates, the data spanned between March of 2014 and December of 2019, with the highest density of data found most recently between late 2018 and 2019. Cultural hubs and government centers contained rich pools of posts, including Faneuil Hall (a historic market) and Boston City Hall (a highly contested architectural landmark and civic building). Touristic locations and public parks also saw considerable activity within the city center. Holidays and celebratory moments saw spikes in activity, such as US Independence Day and Christmas within a central plaza.

After collecting, analyzing, and interpreting the social media data set for emotive characteristics, the results were showcased through an interactive exhibition on the theme of Computational Design at Harvard's Graduate School of Design (see figure 7). Visitors were able to engage with the urban context, change inputs, and provide feedback. Observational data was collected during the exhibition, including commentary and feedback from users.

Figure 7
User demonstrations and activity from the exhibition.

## DISCUSSION & FUTURE WORK

TrendScape was very effective as a tool to showcase transformations and trends across posts and time (related to activity and frequency), though was not as informative in showing how users responded emotively. EmojiScape, however, used emojis associated with each emotive response. This allowed users of this tool to quickly and easily understand how the individual posts related to a place and feeling of that place. As proof of concept, both of these interactive tools were effective in translating a social media dataset into a productive tool to understand the use of public space and extensions of human behavior with location specificity. With the case study focused in Boston, a US city, the project did not give light to challenges related to the European Union's General Data Protection Regulation (GDPR). Future iterations of this work would more rigorously identify how to gather real-time data sets, which had data analysis or tracking permissions from users.

EmojiScape's limitations were primarily found in the realm of available datasets only related to spatial perception. The project utilized a static dataset within a limited timeframe and geographic area. In an ideal circumstance, the EmojiScape tool would be linked to a constantly updating dataset through Instagram's API or similar. Furthermore, the tool would ideally be applied across all major cities rather than a single city as a case study. The project also had limited analysis ability because many of the data points were related not to what people experienced in the spatial context but to arbitrary contents. In addition, the Watson Tone Analyzer API, which was used for emotion analysis, was designed for general use and even originally built for monitoring customer services. These limitations would cause inaccuracies in measuring user perceptions. Ideally, irrelevant data needs to be filtered out through targeting algorithms and the Natural Language Processing model should be trained with a dataset only related to spatial contexts in order to compensate for inaccuracies in the future.

As it applies to usefulness for civic leaders or designers, EmojiScape has the potential to allow for research of historic place-specific activity, while also tracking how physical changes in infrastructure affect emotive changes. As an example, a landscape

architect working on the development of a public plaza would be able to extract a historic and current dataset from that location and site, thus enabling analysis of how people interacted with the site, how they reacted emotively to it, and evaluate the effectiveness of their new intervention as compared to the historic conditions. In its next iteration, EmojiScape could potentially be used to compile a dataset of all projects completed by a specific design firm and notify the firm of new activity and emotive changes through a dashboard. A similar approach could be applied for city planners, who hope to study neighborhoods and the impact of public parks or new public artwork.

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# User-driven Configurable Architectural Assemblies

## *Towards artificial intelligence-embedded responsive environments*

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*The paper theoretically elaborates the idea of individual users' customisation activities to create and configure responsive spatial scenarios by means of reconfigurable interactive adaptive assemblies. It reflects Gordon Pask's concept of human and device interaction based on its unpredictable notion speculating a potential to be enhanced by artificial intelligence learning approach of an assembly linked with human activator's participative inputs. Such a link of artificial intelligence, human agency and interactive assembly capable to generate its own spatial configurations by itself and users' stimuli may lead to a new understanding of humans' role in the creation of spatial scenarios. The occupants take the prime role in the evolution of spatial conditions in this respect. The paper aims to position an interaction between the human agents and artificial devices as a participatory and responsive design act to facilitate creative potential of participants as unique individuals without pre-specified or pre-programmed goal set by the designer. Such an approach will pave a way towards true autonomy of responsive built environments, determined by an individual human agent and behaviour of the spatial assemblies to create authentic responsive built forms in a digital and physical space.*

**Keywords:** *deployable systems, responsive assemblies, embedded intelligence, Learning-to-Design-and-Assembly method, Conversation Theory*

## INTRODUCTION

The concepts of user-driven configurable assemblies to create customised spatial scenarios are starting to be prevalent again with applications of digital fabrication and automation methods for an assembly, employed in architecture in recent decades. Also the recent projects involving certain level of intelligence of devices and building blocks with the ability to create spatial scenarios by themselves explore rule sets predefined by the designer. There are many customisation-related deployable systems, built and modified by users based on architect's proposed combinatorial system of configurations, such as concept of moving adaptive assemblies elaborated by

Bondin & Glynn (2014) or intelligent tensegrity self-assembly components by Hosmer & Tigas (2019). These two projects and a variety of deployable systems are reflected in the text below, in the State-of-the-art section. These systems use automation-enabled processes to discover spatial possibilities and locomotion of the building components to automatically assemble demanded configurations.

Contemporary built environments are facing many challenges, i.e. often changing spatial requirements, a necessity to be customised according to specific criteria (openness, closeness, flexible spatial arrangement) or spatial demands that cannot be predicted and that are addressed directly onsite. In addition, such a system should have capacities to be reconfigured physically and directly by end-users themselves. In response to their stimuli, the assembly may learn the unique demanded scenario defined by the end-user and offer an adequate response within a given conditions of environments.

Therefore, it is necessary to incorporate end-users' perspective into abilities of assemblies to be modified and changed in post-actuation processes of built environments and in an interactive way. Application of deployable architectural systems based on mechanisms and components driven by people's stimuli and embedded intelligence to meet their needs is a strategy where this intention can be achieved. The paper addresses a problem of mass-customisation and uniqueness of spatial scenarios considering users' spatial preferences. It theoretically outlines a method how to incorporate user's demands interactively and responsively, considering important relations between environment, built assemblies and people as end-users in a physical way. The mass-customisation as a process to meet people's needs and demands is an inevitable necessity in a current post-digital era, where the user plays a pivotal role in these activities. An architect's role within this context will mostly rely on a creation of initial rule-sets of an assembly and logic of spatial configurations based on combinatorics, with unpredictable results. An architect will serve here as an idea initiator, mediator, activist and a creator. This idea meets Jean Prouvé's concept of being an architect, who, in fact, serves as a constructor (Wigley, 2017). This paper theoretically elaborates such an approach and outlines a possible route for further development of computational design-related and assembly strategies for intelligence-embedded spatial scenarios.

## *State-of-the-art in deployable systems*

The advent of digital fabrication methods supported by processes-driven design strategies and scripting (Burry, 2011) opened broad opportunities to explore deployable systems in digital computational and physical models incorporating robotics and smart mechanisms and devices, such as in the CREASE project by Mesa et al. (2019). The idea of crowd-driven digital and physical participatory construction methods to address social engagement, customisation and open-ended spatial scenarios is addressed in Bondin & Glynn' s project Morph (2014) as a starting point to deliver a physical prototype capable to interact with its environment. The Morph integrates interactive stimuli initiated by occupants where their role as end-users in the post-actuation processes of built scenarios is inevitable. This allows to outline a scope for participatory design strategies applicable directly on-site in infinite continuous design-to-assembly looping processes. The system is driven by end-users and capacities of assemblies themselves to responsively react to occupants' individual needs. Such an approach positively affects the public space and creates an important space for social engagement of end-users and visitors. Even though the system proposed does not integrate natural resources and materials used are not specifically environment-related, the system counts with the alternative sources of energy to drive the movement for adaptation.

Similarly, the ART system by Hosmer & Tigas (2019), explored the notion of artificial intelligence-embedded moving agency creating fully autonomous scenarios pre-defined by the designer in computational simulation models and small-scale

prototypes. Although these artificial intelligence-driven assemblies created unique scenarios, the implementation of original stimuli taken and learnt from end-users as occupants to meet their individual needs or requirements is problematic. An advanced electronic setup based on robotic actuators requires a specific experts' attention, probably unclear and peculiar to operate with by a lay person. This can be possibly achieved digitally, via user interface supported by the computational design framework. Both projects use the process of deployment for the main structural elements of the moving component. Although Hosmer & Tigas (2019) developed successful prototypes of intelligence-driven components, a certain level of technological complexity is present, which is a challenge how to overcome this level of complexity if dealing with real non-experts occupants.

The idea of deployable adaptive and flexible typologies for built environments is not new. Inventor Buckminster Fuller [1] and later architect Emilio Pérez Piñero applied these systems extensively into hierarchical spatial structures in a variety of projects (Escrig Pallares et al., 1996). Félix Escrig investigated Piñero's systems to be applied as contemporary architectural interventions (Borrego, 2016) enhancing Piñero's components. There are several examples proposed integrating deployable folding mechanisms, mostly driven by a human force and energy applied to modify the overall form of hinged and folding mechanisms capable of expanding and contracting without colliding with neighbouring components. Stadium constructions, theatres and roofs utilise mechanical joints and linear elements extensively. Architect Cedric Price investigated customisation and "kit-of-parts" approach in his housing projects [2], or integrated flexibility of spaces in his famous Fun Palace (Glynn, 2005) [3], addressing flexibility, mass-customisation and open-ended construction framework [4].

The structures integrating so called *auxetic* properties, such as KinetiX (Ou et al., 2018) or Hoberman's Sphere (Hoberman, 1990)[5] operate with simple mechanisms embedded into the structural system. As such, the system can be reshaped, expanded and changed in its size and in a physical profile based on a variety of transformative movements of its components, possibly aggregating as self-autonomous components, previously explored by Tibbits (2017). Overvelde et al. (2016) and Soft Robotic Matter Group investigates self-driven deployable systems either by using robotic actuators (Mesa et al., 2019) or gravitational, pulling or pushing forces to reshape the assembly of unit cells [6]. All these systems integrate capability of the component to be morphed and reshaped into a different state. The Morph tetrahedron also reflects Greg Lynns' ideas of a building which operates as a robot itself (Lynn, 2016), reacting on a specific demands and having a capacity to be reshaped and reconfigured according to spatial demands. However, this opens a question, whether current technological advancements in robotic industry and construction sector are capable to deal with such processes in real 1:1 scale, as all these kinetic assemblies are in a state of small-scale or medium-scale prototypes.

The intelligent discrete components, capable to learn from the inputs and users' profiles, may create flexible adaptive landscape or a spatial configuration within the existing building or a given urban public space creating a unique spatial "landscape", flexible, movable and topologically changeable, as argued by Stephen Gage (conversation with the author, December 11, 2019). In addition, the assembly may incorporate hierarchical structure of the assembly operating with different characteristics of the components and hierarchical complexity.

### *Reflection on Gordon Pask's Conversation Theory*

Following the idea of customisation of public urban or architectural spaces with a deep social engagement of its occupants (Bondin & Glynn, 2014), this opens a broad range of new research possibilities how a public space can be perceived and what is the role of an end-user in post-actuation processes of

built environments. Gordon Pask's Conversation Theory (Haque, 2007) elaborates the aspects of interactivity between human and machine (i.e. a device), between two machines (devices) and between human agents themselves. Such a responsive communication creates unprecedented opportunities of human and robot interaction bringing artificial intelligence capable to learn from users' stimuli and response. This allows the device to create unique and unpredictable responses meeting each individual's inputs and needs, always ready to adapt to new conditions or purpose and produce a variety of spatial solutions to answer on different requirements. This is outside of the idea of typical participatory design, where there is always a need for a consensus between interested parties. Reflecting existing developed systems addressing a variety of spatial requirements and flexibility, it is necessary to claim that Pasks' idea of being "*able to account for an explicitly human contribution*" would be essential to continue with the development of responsive building components for built environments for the 21st century. John Frazer and his team (Frazer, 1995) in his approach implemented this concept providing electronic devices for end-users' participation in the Self-builder Design Kit project.

Architecture capable to learn from its occupants just as occupants can learn from architecture may bring relevant cultural and spatial solutions to cover intelligence-based built scenarios based on simple interactions to create more complex results, beneficial for inhabitants themselves. Thus, a "conversation" between human and artificial components can emerge, between an individual, an environment and a building device, not pre-programmed or predefined for a finite state, but always ready to be reconfigured in a flexible way and bringing "*novel responses in unpredictable and novel situations*" (Haque, 2007). This enables occupants to share performative and environmental characteristics to construct unique and tailored habitable spatial scenarios.

## PROSPECTIVE FUTURE SCENARIOS

In the 21st century-built environments a user-centred approach needs to be taken in the design and post-actuation processes to fulfil uncertain users' demands. Immediate environmental properties as well as unique individual requirements are needed to be considered during the design, configuration and assembly processes, where the user plays the main role in assembly and post-assembly activities. As such, the assembly process equals the design process with a constantly reiterated feedback loop. The artificial intelligence will certainly help in these activities, however, not as a main driver, but as an additional ability of the building component to be morphed and re-assembled informed by a specific user profile meeting his or her demands. The idea of flexible *auxetic* properties of the building components might serve as an initial strategy employing mechanics driven by manual, natural or mechanical forces, enhanced with the capability to learn from predefined states, from the users' inputs and deliver customised scenarios, proposing specific situation-related states. The mutual intelligent interaction, as argued by Gordon Pask, will yield appropriate scenarios bringing new spatial qualities, responding to previously learnt states of the building components, capable to interact between themselves, humans and within a given environment.

In fact, this design problem of customisation brings also the question of precision and technical and computational requirements. Is the building component a machine? Or a digital (virtual) post-machine? There is always a tension between anthropocentric and digitally driven "technocratic" approach and there is no right or wrong direction for further move.

### *Learning-to-Design-and-Assembly Method*

The research proposes a new method called "Learning-to-Design-and-Assembly" (LTDA) for users' participation to create spatial scenarios that may evolve and be changed in time. For that reason, a novel type of spatial typologies as user-driven as-

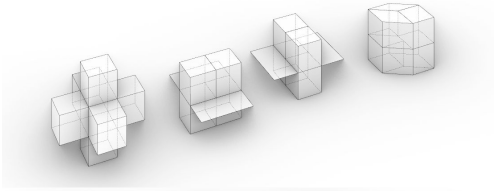
semblies are being developed to enable users to construct unique and tailored habitable spatial scenarios. The LTDA method will incorporate artificial intelligence-supported learning process and decisions in mutual interactions between humans and building components capable to be morphed, components between themselves and building components interacting with the given environment. Thus, a "conversation" between human and artificial components can emerge, between an individual, an environment and a building device, not pre-programmed or pre-defined for a finite state, but always ready to be reconfigured in an adaptive way.

There are two core features of the proposed user-driven assemblies, which the LTDA method will operate with: a physical kit-of-components based on auxetic principles for morphing and reconfiguration of an assembly integrating manual, automatic or semi-automatic operation; and, artificial intelligence-enabled logic and integration based on self-generation of interactive spatial configurations and following unique user profiles. As such, the LTDA method follows the specific users' individual requirements and properties, which are educed from the users' behavioural patterns and their habits. These are self-generated and condensed in a spatial scenario, physically present in situ. The LTDA method will allow users to physically participate on a construction and configuration of spatial scenarios delivery, often as a result of improvisation and collective or individual decisions made.

### *Computational strategy*

An initial computational framework is proposed to accommodate a strategy for the LTDA method implementation, consisting of following steps:

- component definition of configurable parts utilising auxetic principles of an assembly;
- a set of initial spatial configurations definition by the designer in the computational model;
- data mining process based on users' submissions via online interface (this process is temporarily substituted by evolutionary generation method for the purpose of this paper);
- data set integration and deep learning implementation for spatial assemblies delivery.



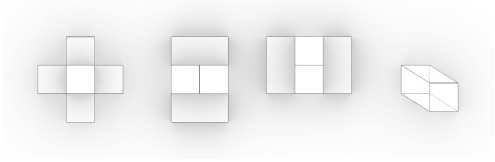


Figure 1
The definition of configurable cell units, developed by Overvelde et al. (2016). This paper investigates configurable units of the extruded cube to generate a variety of spatial assemblies for urban tower blocks utilising evolutionary generation method.

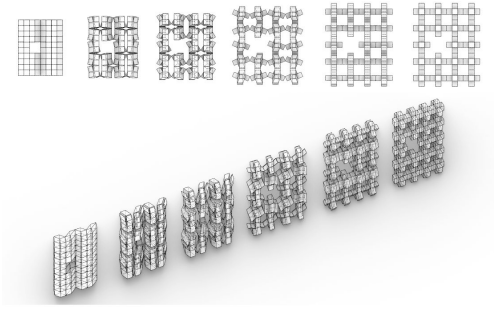


Figure 2
Auxetic behaviour of the structure. The structure has the capacity to expand into a different spatial state. Each component is adjustable and configurable.

The concept of spatially configurable assemblies incorporates cell units capable to transform and morph to a variety of states, implementing the principle of *auxetic* expandable structures. The shape of the unit had been previously investigated by Overvelde et al. (2016), analysing the extruded cube unit cell and its state variations (Figure 1). For the purpose of this paper, this cubical cell unit and its configurable states were taken for further testing and analysis of possible configurable assemblies, envisaging an urban scale of units for configurable urban tower blocks (Figure

2). Therefore, spatial configurations are created either by the set of components or the component unit itself creates the spatial scenario, depending of the component's and scenario's scale, scenario definition, spatial demands and component's ability to be deployed or morphed.

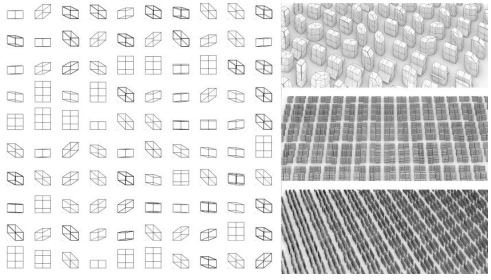


Figure 3
Generation of the configurable units as components for tower assemblies.

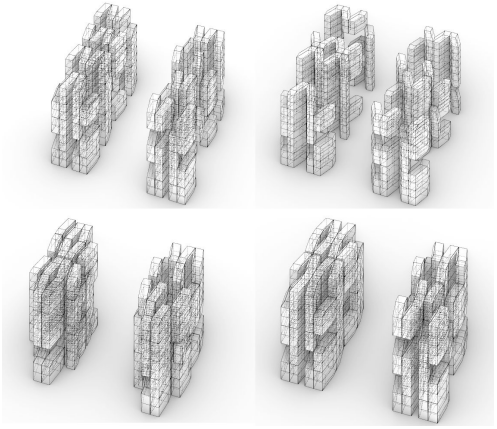


Figure 4
The spatial assembly of configurable units utilising auxetic properties of the structure. The structure behaves as spatial origami.

Hosmer & Tigas (2019) developed a computational framework utilising deep learning methods with ML agents implemented in the UNITY game engine to deliver spatial geometrical scenarios [7]. The process of learning which ML agents accommodate uses the Google TensorFLow platform running on GPUs for massive deep learning processes from predefined datasets [8]. Such datasets can be delivered from end-users in the first instance and the system can learn from these preferred solutions to artificially generate novel spatial solutions. However, this paper does not present the utilisation of current machine learning methods for the spatial scenarios delivery, as this will be tested in the next phase of the research. For the purpose of this paper, the first initial generations of possible spatial solutions were tested utilising the evolutionary generation method based on the Wallacei tool [9]. This method was utilised to generate big amount of data, instead of users' data mining. These can prospectively mimic and substitute the users' preferred scenarios and can be used for further deep learning implementation in the future research (Figure 3).

The evolutionary method delivered a population size consisting of 5000 solutions in 100 generations of configurable assemblies and meeting the particular volume size and dimensions of the configurable unit as a design objective. Each spatial solution operates with a different or similar state of each particular unit (Figure 3), creating unique tower assemblies (Figure 4 and 5).

## DISCUSSION

Several deployable and self-assembly systems were described and reflected, such as the Morph Tetrahedron to discuss aspects and criteria for customisation, social engagement of users and environmental responsiveness. Further, the artificial intelligence-driven tensegrity assembly system (ART) was discussed in the scope of customisation and the notion of learning approach of the automated or semi-automated assembly processes, pointing out a necessity to integrate end-users' role in the Learning-to-design-and-assembly method of the building process.

The test of the behaviour of auxetic principles of the structure was conducted computationally to understand the behavioural characteristics of the simple units in the computational model and to deliver generations of possible spatial scenarios which mimic the datasets, prospectively submitted by end-users (Figure 3). Next stage of the research will utilise these datasets to test the deep learning

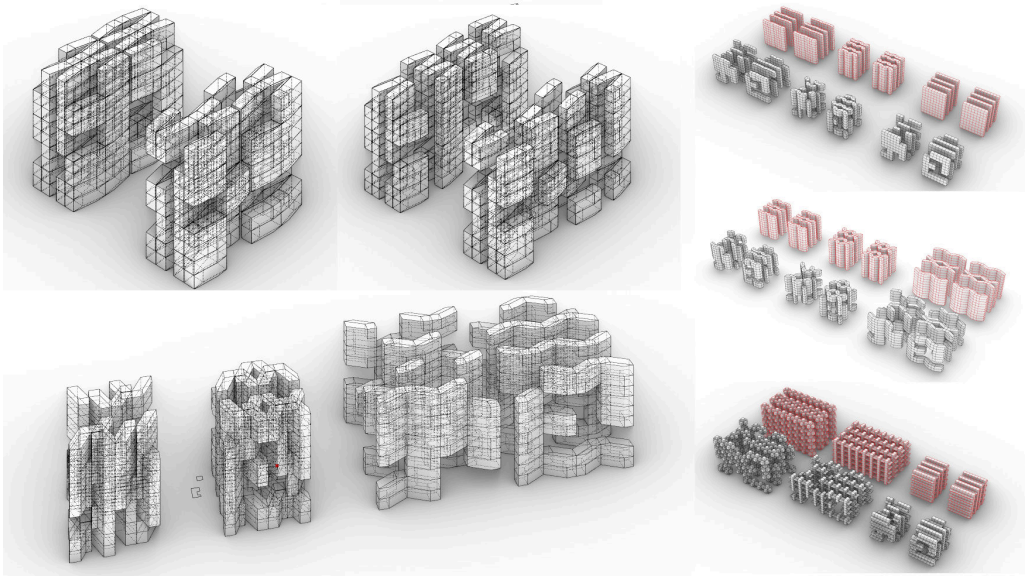


Figure 5
Spatial assemblies generated by evolutionary algorithm to meet volumetric objectives (size, dimensions) and integrating auxetic principles of an assembly.

method running on the TensorFLow platform to deliver artificially-generated spatial assemblies, incorporating specific spatial features.

Utilising auxetic characteristic of the structure to be expanded or morphed according to applied forces and external sources of energy, the assembly systems will be able to integrate more diverse scenarios into several subsystems under one emergent structure without any loss of notion or expression of the architectural quality and integrity. This will deliver open-ended collaborative and sharing platforms operating with several levels of responsiveness allowing design participation on-site. In that regard, the research can follow these directions further, concentrating on user-driven assembly processes, operating with discrete intelligent components responding to users' demands more comprehensively.

But how to achieve this integration encompassing technological advancements in computation and artificial intelligence? To address mass-customisation in physical built environments, the new forms of "Learning-to-design-and-assembly" building procedures need to be applied instead of standard and usual designer-client-contractor relationships. The new modes of sharing economies might offer alternative solutions for participation, planning, design and construction, where the emphasis is given on the activation of users themselves with their values, knowledge and skills. On the other hand, the intelligent building components have to offer appropriate response meeting end-users' demands and following spatial, economical, aesthetic, and, sustainability-related criteria for the construction and assembly. Architects, as constructors and activators in these processes play a crucial role as they navigate, inform, supervise and promote these intentions, helping the users to orient them in the process.

The first step towards achieving this integration and pursuing these intentions can start with less technocratic solutions. Components may involve auxetic principles, material memory and can be based on simple moving forces, applied by the users

themselves. Several intelligence-enabled states of the building components and degrees of an assembly may yield a variety of spatial outcomes. The components delivered on-site as participatory constructions and assembled by users in semi-automatic or fully automatic processes may learn their own new spatial states in a continuous and open-ended feedback looping process. However, a comprehensive research in this field still needs to be conducted to fully embrace new potentials of built and responsive environments for the 21st century in the era of uncertainties.

## ACKNOWLEDGEMENT

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# Pattern-driven Design for Small Public Spaces

## *An analysis of pattern books and toolboxes*

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*Urban spatial patterns that can enhance the city's cultural, social, environmental, material and structural performance advance beyond the old notions of design patterns by incorporating the digital design. Pattern books such as ``A Pattern Language'' are revisited and toolboxes /toolkits are used in contemporary urban designs by laboratories and offices. The aim of this paper is to analyze the particularities and congruencies between some systems of patterns, pattern books, toolboxes and toolkits aimed at small public spaces, also considering the context of digital culture. The methodology proposed is the construction of a taxonomy that relates and classifies these selected patterns, by these following steps: a) selecting of patterns applicable to small public spaces; b) classification of patterns by ``type'' (location, behavior, processes and design components) and by ``driven designs'' approach (data-driven design, performance-driven design, and material- driven design) and relation to the recurrences of patterns between the systems; c) making and inserting in the taxonomy platform a table of elements and connections; d) filtering by classes for analysis. From the results obtained in the visualizations, it is possible to consider a larger volume of ``location'' type patterns and a smaller volume in ``processes'' indicating a field that can be developed.*

**Keywords:** *Urban patterns, urban toolbox, small public spaces, data-driven design, pattern language*

## 1. INTRODUCTION

Using patterns that emerge from a coherent system of rules is part of the history of architecture, from historical treaties to algorithms and shape grammars. A recurring issue, therefore, is the hypothesis that using patterns would lead to the standardization of architecture. Patterns, on the contrary, are ways to take advantage of proven design strategies that bring out variously coherent and inexhaustible solutions from a complex system. Technology, binary systems, in short, digital also works through commands that are based on patterns.

According to (McGrath and Marshall 2009), the new urban design patterns are in the way of cities as living organisms, which deal with rapid urbanization, with the movement of people, climate change,

such as digital and mobile communication technologies and intelligent infrastructures. The compilation and the sharing of these patterns systems can be found through pattern books, toolboxes or toolkits that users and planners can merge patterns or adapt them to their reality.

The aim of this article is to analyze the particularities and congruences between some systems of patterns, pattern books, toolboxes and toolkits aimed at small public spaces, in order to understand the approaches present in each one, also considering the context of digital culture. This article is part of broader research on spatial patterns for small public spaces as a way to guide a design process with driven design approaches.

## 2. SYSTEMS OF URBAN SPATIAL PATTERNS

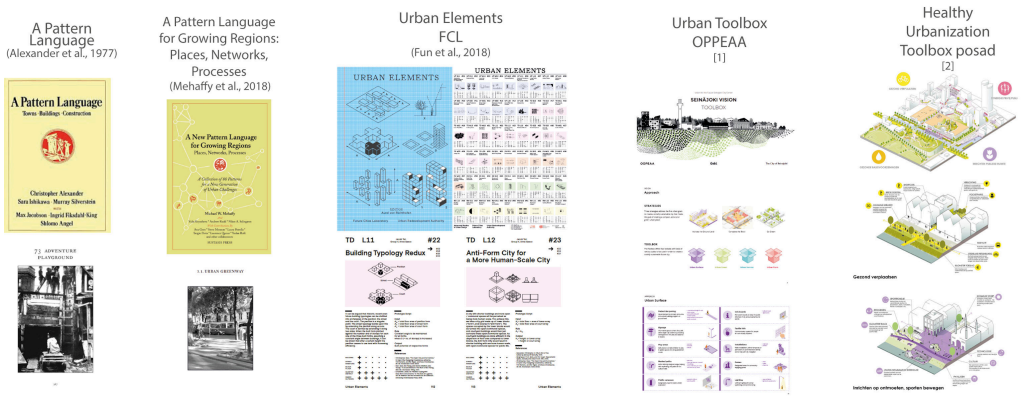
Concepts and theories from different eras can be placed as systems of patterns, treaties, theories about the order, symmetry, and proportion (Mitchell and Celani, 2008). In a historical perspective, (Gehl and Svarre, 2013) reflect on patterns centered on human behavior and social life in small urban spaces (Whyte, 2001, 2012), on the importance of spaces between buildings (Gehl, 2011), on the habitable and walkable character of streets (Appleyard et al., 1981; Jacobs, 1995) and basic activities such as walking, sitting and walking (Gehl and Svarre, 2013). Many of these publications are still, today, based on studies of public spaces and strategic city planning.

One of the theories using patterns most significant was created in 1977, the book "A Pattern Language" (figure 1), from theories by Christopher Alexander, which lists 253 spatial patterns that form a network that connects them, with the intention of helping participatory processes. According to (Garcia, 2009) based-on (Alexander et al., 1977) , other spatial patterns about the city emerged at this time with some of the precursors of public space studies, such as (Venturi et al., 1977), Jacobs (1961) and Lynch (1960). Pattern systems in books format are still lines of research in the design of urban public spaces, for example, "A pattern language for growing regions: places, networks, processes" (figure 1) by (Mehaffy et al., 2018) resumes presentation structure of "A Pattern Language". The 80 standards proposed in the new book are focused on the quality of the development of regions around the world, based on the guidelines of the New Urban Agenda, proposed by the United Nations (UN).

Another current urban pattern system was developed by the Future Cities Laboratory (figure 1), from Singapore-EHT, in a work called "Urban Elements" (Fun et al., 2018). According to the book, urban elements form the urban tissue and usually refers only to the physical blocks of the city, buildings, and spaces between them, which can be combined. However, just like (Alexander et al., 1977), they argue that these urban elements do not work alone, as they become useful in a context, as well as in a language that interrelates elements through principles and rules. "Urban Elements" considers the city as a metabolic system in which the city's physical tissue interacts with various flows based on the following themes: (UF) Urban Form; (TD) Typology & Density; (FU) Function & Use; (ES) Eco-Systems Service; (EM) Engaging Mobility; (SE) Sustainable Energy.

Not only research groups but also some offices developed and applied some urban spatial patterns through toolboxes and toolkits. The Finnish office OOPEAA developed in collaboration with Gehl and the city of Seinäjoki (figure 1), an urban toolbox for future interventions at various scales. With the aim of creating accessible and inclusive urban designs, they created four main sets: Surface, Green, Services and Urban Form [1]. The Dutch office Posad developed a toolbox aimed at healthy urbanization grouped into four categories: a) healthy movement around the city; b) public spaces designed for exercise, recreation, socialization, and sport; c) synergy between public and private spaces; and d) healthy basic facilities. The "Healthy Urbanization Toolbox" (figure 1) from the Posad office was applied in the city of Utrecht as a form of urban development targeting cities and healthy citizens [2].

Figure 1
Systems of Urban Spatial Patterns




## 3. DIGITAL CULTURE IN URBAN DESIGN

The issue of design today, according to (Oxman, 2017), is based on explicit processes, which are not a simple triggering of steps, but systemic and parametric views, thinking of a society in constant transformation. Digital culture in architecture and urban design is part of what some authors call "intellectual revolution", in a search for more objective approaches and a multidimensional vision (Kotnik, 2017; Picon, 2015; Carpo, 2017). Like the rhizomatic thinking proposed by (Guattari and Deleuze, 2000), digital culture points to a search for understanding connections, heterogeneity, mutation, and information in order to understand the relationships and controversies present in the process of building cities.

With the emergence of digital design, this systemic character and the growing volume of information available to architects and planners, some niches of design process began to appear, mostly called driven designs: data-driven design, performance-driven design, citizens -driven design, material-driven design (Oxman, 2012, 2017; Kolarevic, 2003). Although the term pattern-driven design is not widely used, many of the pattern systems developed today, can or are already guided by these driven design and digital culture approaches.

Data-driven design is one of the most comprehensive, in an emerging view of evidence-based and data-driven processes, in which digital design is the great ally in its processing capacity (ARUP and RIBA, 2014). The design data is the objective information that the designer uses: analyses, patterns, and data that involve a large number of issues considered in the process. Comfort and performance, laws and regulations, user behavioral patterns, mathematical analyses based on topology, tectonics, demographic data, budgetary issues, and many other data available today, that increasingly lead society to understand and treat large volumes of data generated in the city.

Ratti and Claudel (2016) and Offenhuber and Ratti (2014) refer to the information generated in the city as a fundamental source for research. According to ARUP and RIBA (2014), cities are beginning to realize the potential of new agendas, such as Smart Cities (Leite, 2012; Townsend, 2014, when using information and communication technologies, allowing the optimization of urban metabolism and the opportunity for collaborative processes (Picon, 2015). With new digital technologies, the reality of design and citizen participation has easy access to the internet, smartphones, GPS and large availability of data (Gehl and Svarre, 2013; Mitchell, 2000).

## 4. METHODOLOGY

The proposed methodology is the construction of a taxonomy that relates and classifies the patterns for small public spaces present in a given corpus. This analysis is one of the steps towards broader research that seeks to develop a new system of patterns for small public spaces consistent with the new demands of the digital age. Therefore, the construction of this taxonomy allows discussing some of the paths that urban spatial patterns have been developing.

The selection of the corpus was based on four pillars: temporality, location, presentation, and authorship (table 1). A succinct number of systems, which could represent diversity, works developed in different periods, countries, presented in different formats, in addition to contemplating authorship of architecture offices, laboratories, and theoretical authors. The corpus chosen was the selection of five systems presented in section 2: "A Pattern Language" (Alexander et al., 1977), "A Pattern Language for Growing Regions: Places, Networks, Processes" (Mehaffy et al., 2018), "Urban Elements" (Fun et al., 2018) , "Urban Toolbox" [1] and" Healthy Urbanization Toolbox" [2].

Table 1
System Characteristics

| | Date | Country | Format | Autorship |
|---|---|---|---|---|
| A Pattern Language (Alexander et al., 1977) | 1997 | EUA | pattern book | academic |
| A Pattern Language for Growing Regions: Places, Networks, Processes (Mehaffy et al., 2018) | 2018 | Sweden | pattern book | academic |
| Urban Elements FCL (Fun et al., 2018) | 2018 | Singapore | pattern book + scripts | academic |
| Urban Toolbox OPPEAA [1] | 2019 | Finland | toolbox | office |
| Healthy Urbanization Toolbox posad [2] | 2015 | Netherlands | toolbox | office |

According to (Cledou et al., 2018 )taxonomy is the science of classification and has the ability to transmit information in groups, establishing their relations and providing a framework for discussion. In the understanding of urban space, classification helps to reduce complexity, as it brings out the essential and discards the non-essential. Classification is a necessity for filtering empirical and complex elements, like urban uses, because it promotes the investigation of the characteristics of certain elements in order to determine ways of grouping them based on their similarities (Pissourios and Lagopoulos, 2017).

Taxonomy seeks to classify and relate the patterns of each system. The validation of using taxonomy in this methodology occurs through the consistency of the proposed classes and the wide use of taxonomies in the field of architecture studies. The process followed these steps: a) selection of patterns applicable to small public spaces within each system; b) classification of patterns by "work", by "type", by the "driven design") and the relations among them ; c) making and inserting a table of elements and connections on the Kumu.io platform; d) filtering by classes for visualization and analysis.

The platform chosen was the online network visualization tool Kumu.io, cause it is a friendly and accessible interface, which allows the use of colors and interactivity when viewing connections.

### *4.1 Classification*

**Type.** The classification by type was thought to understand which focus and stage of the design process each pattern fits, divided into four classes (figure 2).

Location - patterns that show relations with other urban elements, without actually indicate how the components should be designed.

Behavior - patterns that show the urban uses and how they contribute to the liveliness of the public space.

Processes - indicate the way to do the design, analyses, tools or data collection.

**Work.** This class identifies which system that pattern belongs to, showing which system has more patterns applicable to the small public spaces (figure 3).

**Driven Design.** Design Components - refers to the patterns that actually indicate rules for the design of an urban component.

Figure 2
Taxonomy visualized by the "type" class

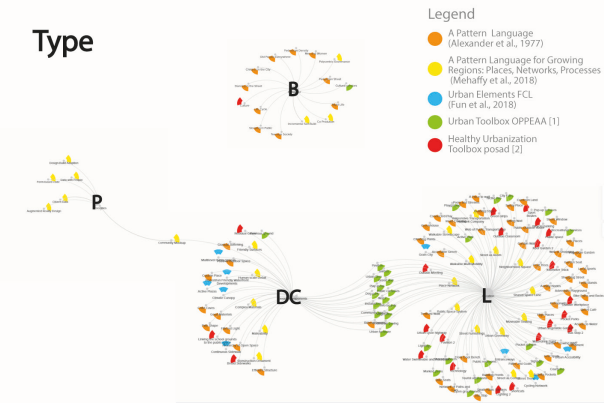
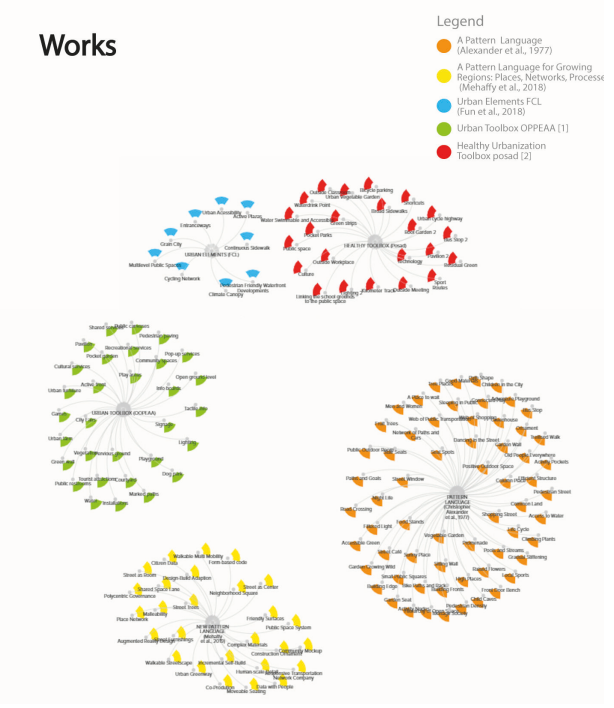
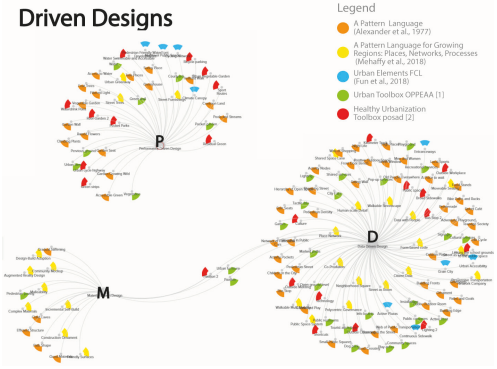
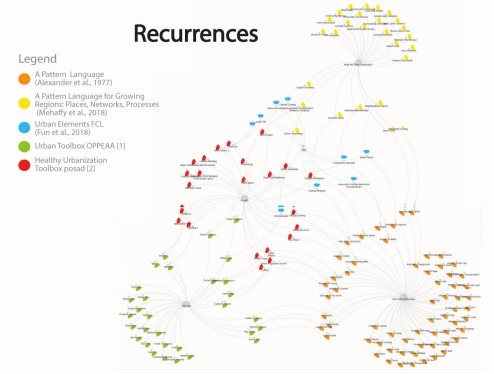



Figure 3
Taxonomy visualized by the "work" class






The class driven design classifies which approach fits better on that pattern even though there is no discussion of digital culture, based on three classes: data, performance, and material (figure 4).

### *4.2 Relations*

It was necessary to create a new taxonomy to assess just the relations between the recurrences of patterns with the same theme, without classes, in order to verify which patterns are more commons (figure 5).

## 5.RESULTS

The aim of this paper is to analyze the particularities and congruencies between some systems of patterns, pattern books, toolboxes and toolkits aimed at small public spaces, also considering the context of digital culture. The analysis benefits from taxonomy when it shows graphically the concentration of patterns in each class.

The congruence with larger volume in "type" class was formed by the patterns classified as "location", followed by "design components", "behavior" and finally "processes". The larger volume of "location" patterns may indicate a common effort by systems to present the relations between urban components, without intending to treat the design of the components themselves. These combinations in a digital design context suggest more qualitative relations, in a parametric language more aligned with combinations type of if/and/or between the elements. The lower volume in "processes" indicates an aspect low explored by these systems and that can be improved, in order to incorporate more ways to design the city. Especially talking about toolboxes in the context of digital culture, the presentation of digital processes and digital tools for the construction of these new cities becomes essential. The generative component tool DeCodingSpaces Toolbox [1] [4], which is part of the "Urban Elements" research, is an example of this new kind of tools but has not been included in the analysis of this article. The analysis of generative components like this demands a deeper study, both theoretical and practical, about parametric and algorithmic design processes in urban planning.

The large volume congruence in the "driven design" class was formed by patterns classified as "data-driven design", followed by "performance" and "material". The accumulation of patterns in "data-driven design" indicates the potential of this approach, but it also indicates the breadth meaning of the term. Therefore, there is a need to understand what data are truly useful for city planning and how they can work together. The low concentration in "material driven design" is also a field that can be more incorporated into toolboxes and pattern books, together with discussions about new materials and new ways of building emerging in the digital age.

Figure 4
Taxonomy visualized by "driven design" class

Figure 5
Relation of recurrence

In the "works" class, it is possible to visualize the group with the largest number of patterns compatible with the scale proposed, small public spaces. The work "A Pattern Language" by (Alexander et al. 1977) has the larger number and the set "Urban Elements" of FCL-EHT Singapore [1] has the smaller. However, it is necessary to consider that the "Urban Elements" system presents a script set that allows the creation of new urban patterns, but which will not be addressed in this article.

In the analysis of the relation between the systems, it was possible to visualize which patterns are most repeated, showing which are the most recurring questions. The patterns that refer to the theme of sidewalks and walkability in the streets were the most recurrent, appearing in 4 of the 5 systems of the corpus. With recurrence 3 appear patterns that indicate qualities of outdoor public space; active entrances to buildings; urban vegetable gardens; pocket gardens; spaces for culture and local sports.

Regarding the particularities of each system, the taxonomy shows that the work of (Alexander et al. 1977) presents a large number of patterns of the location and behavior class because the book's proposal is to establish relations between urban qualities and the historical context of behavioral analysis. The work of (Mehaffy et al., 2018) has an interesting feature, as it is the only one that presents process patterns. The system that most presents the design components class is the authoring system of the OOPEAA office, with a wide variety of components that can contribute to the liveliness of these urban spaces.

## 6. DISCUSSION AND CONCLUSIONS

The use of interactive taxonomies tools allows visualization and graphic manipulation, a difficult task using only books and infographics. The main contribution of this study is to relate systems of patterns from different contexts, in order to analyze a larger number of approaches on the public space, in discussions that complement each other. From the results obtained in the visualizations, it is possible to consider a larger volume of "location" type patterns and a smaller volume in "processes" indicating a field that can be developed. In practice, this study can contribute to architects, when it encourages them to include patterns in current approaches, helps to visualize which are the most recurring patterns in different discussions about urban spaces, and shows paths to study the new public space production processes.

The study of public space through patterns also has limitations, a system of patterns is able to emerge just a few layers of information from a complex reality of public spaces, because some social narratives, historical and political facts need to be associated, otherwise, this can decontextualize the patterns of local reality.

The initial effort to relate these sets of patterns is a step towards understanding the most coherent paths for urban spatial patterns. This ongoing research suggests some next steps: a) integrating new systems and new digital tools into taxonomy; b) understanding of the most consistent patterns for the local development of these small public spaces in the context of digital culture; c) development of a new system of patterns that adapts and references others; d) study of a friendly platform for making manipulating and share them.

It has not yet been possible to incorporate sets of generative components, scripts, plug-ins, and sets of algorithms in this study. This would be one of the future steps, in a depth study about the role of these digital tools in generation and adaptation of new patterns.

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[2] http://posadspatialstrategies.com/projects/gezonde-verstedelijking/?lang=en
[3] https://www.arup.com/perspectives/publications/research/section/designing-with-data-shaping-our-future-cities
[4] https://toolbox.decodingspaces.net/

# Reasoning in Common Data Environments

## *Re-thinking CDEs to enhance collaboration in BIM processes*

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*In BIM processes, the concept of Common Data Environment - CDE - has often been depicted as a key element for successful collaboration and information sharing among different actors but, in current practice, acts as a mere documentation repository ineffective for true collaborative purposes. Therefore, the idea of CDE seems to be overrated on the one hand and unexploited on the other, while effective collaboration is still far from being decisively supported. To overcome this lack, the present research focuses on the definition of a new generation of CDEs, enhanced with an information level for knowledge integration provided by different information carriers such as models and datasets. The paper discusses its development through a graph database platform and dedicated methodologies for data retrieval and query, to verify coherence and consistency of information among different models.*

**Keywords:** *Collaboration in AEC processes, Common Data Environment, Graph Databases, Building Information Modeling, Queries and data retrieval*

## INTRODUCTION

In current BIM-enabled AEC processes, Common Data Environment - CDE- has been considered as a key element for successful collaboration and information sharing among different actors and stakeholders. The UK government strategy implies its adoption within the BIM Level 2 scope and some administrations are progressively mandating its implementation in AEC projects. At present, despite a large amount of CAAD research in the field of Collaborative AEC Design process, the most spread structure of CDE is the one proposed in the PAS 1192 (2013) and ISO 19650 (2018) norms, composed of different areas (WIP, Shared, Published, Archived) where project documentation is made selectively accessible to different stakeholders. Relying on this structure, some software industries have proposed their platforms, usually cloud-based, such as ProjectWise (Bentley), Aconex and, more recently, Autodesk BIM 360. As we look at CDEs how it is described in these norms and it has been implemented a big ambiguity, at least from the CAAD research perspective, arises: are we

dealing with data or are current CDEs acting as documentation, although shared, repositories? And, as a corollary, is this CDE structure effective for collaboration purposes? At present, full potentials of the idea of CDE seem to be unexploited, while effective collaboration among AEC processes actors is still far from being decisively supported by CDEs. In the context, this research investigates new methodologies for data, information and knowledge unified formalization in CDE, based on graph databases, to improve coherence, reliability and accessibility of information stored and shared, as well as improving quality of the integration of models, documents and other information carriers that contributes to the central core of data acting as a reference. It essentially focuses on the addition of an information level in current CDEs and discusses the use of graph databases as a way to successfully implement and manage it.

## STATE OF THE ART

In the eCAADe scope and, more widely, in the CAAD and BIM world, much research has been focusing on the integration of Building Information Modeling, information and knowledge ontologies (Cursi, 2017) and linked data as a way to drive, standardize and extend content and semantics of AEC informative models. Potentials of this approach have been demonstrated by research works like the one from Beetz (2005), Pauwels (2015) with a progressive extension of the application to built heritage field (Simeone, 2019) (Di Mascio, 2013). In this field, the development of IFC-OWL ontology has represented an important shift, introducing a reference ontology for AEC entities formalization for interoperability purpose and as an extendable base for domain-specific semantic enrichment of building information models. Similarly, some research has focused on the adoption of information ontologies as an approach to improve knowledge sharing and collaboration between different actors and disciplines (Jelokhani-Niarak, 2018) (Zhong, 2018). This is particularly relevant for this research since it targets one of the main intended features of CDEs: collaboration through comprehensive, coherent and interrelated knowledge (Carrara et al., 2017). If compared to this research direction, research in the CDE field has been quite static. The concept of CDE was created in the IT field as a centralized, unique set of data for any kind of project that requires collaboration and mutual accessibility to data. Later, the concept of CDE has shifted to the AEC field to define the single source of truth for design development, shaped accordingly to major steps in the delivery of an AEC project. On one side, its basic structure and functioning rely on the original framework provided by BS PAS 1192 norms, while research has mainly investigated procedural aspects of CDEs with only partial attention to methods and tools to enhance and ensure the quality, interoperability and richness of the stored content. On the other side, AEC software houses have spent much effort on CDE development, often to improve integration with their proprietary authoring software or to provide scalable, cloud-based solutions for AEC projects. As a result, CDEs are currently used as documents storage environments, with additional metadata progressively introduced to solve documents-controlling common issues such as accessibility, revisioning, file codification, issuing dates, etc. In the last years, the development of tools such as Autodesk Forge has made possible to extract and elaborate stored information directly in the cloud environment, also to cross-link and compare different models (Yan, 2017), (Preidel, 2016). Nevertheless, this approach can be only considered a palliative that relies on the extraction of data, while a few efforts have been made regarding shaping and structuring data, information and knowledge - modelled in the bim model or adjunct in a database - to ensure horizontal reasoning in the CDE. This lack in current CDEs is progressively emerging in the AEC practice, and linked data methodology represents a potential solution that needs to be further investigated (Werbrouck, 2019).

## INFORMATION GRAPH DATABASES FOR NEXT-GEN COMMON DATA ENVIRONMENTS

In CDEs, two main levels can be usually depicted: 1) the information carrier level, and 2) the data/information level. The first one comprises the different kinds of documents, models, reports, calculation notes, etc. that support data formalization and representation and that are usually produced, uploaded, edited, and accessed by different actors. The second level, instead, refers to all elementary data and information, formalized in the information carriers following discipline-specific methodologies and representation structures. By analyzing current CDEs applications, it is clear how CDE platforms mainly focus on the information carrier level, in some cases specifying a simplified set of horizontal relationships among different documents to indicate which of them are related or "linked". No coherence and actual correspondence among data stored in those information carriers are declared, checked, and ensured, and, therefore, CDEs usually result in heterogenous, incoherent, and unreliable information storage. While information ontologies have shown great potential in abstracting entities and relationships, at present data and information are currently managed in BIM software through relational databases that make the entire data structure too rigid and difficult to manage for AEC design process, in particular when those databases are structured based on proprietary software requirements. This issue has been discussed in the IT world, where an alternative approach, based on no-SQL databases, and in particular graph databases, are progressively being adopted, in particular for knowledge formalization and creation of *data lakes* that deal with complex *data patterns* rather than *single data*. In this context, this research proposes and assesses the use of graph databases as a way to access and make homogenous, flexible and queryable the data provided by different information carriers in the CDE, in an integrated way. Among the different advantages of the adoption of graph databases over RDMS (Relational Databases Management System), three are particularly relevant for our scope: 1) focus on relationships, that allows users to depict them from each model and to create new relationships between different entities of different datasets; 2) flexibility, that allows the same data model to be applied to the different dataset stored in a CDE; 3) easy evolution on time, that can adapt to the evolution of the project models better than any RDMS, usually static after the formalization of the conceptual model.

## THE ENHANCED COMMON DATA ENVIRONMENT SCHEMA

In this proposed framework for a new generation of CDEs, this information level developed through graph databases is mainly an environment where information, derived from different information carriers through a process of data extraction, selection, and translation, is represented in a homogenous way, structured and compared. To provide this required homogeneity, the proposed Information Level has been conceived and implemented relying on the use of Information ontologies, while a general ontology structure, based on previous research developed by this research group, serves as an ontology template for re-formalization of data extracted by the different Information Carriers (Simeone, 2019). As described in figure 1, the passage from the heterogeneous formalization of the information carriers to the homogeneous and common Information level requires two crucial passages:

1. Data selection and extraction;
2. Data re-formalization and re-structuring in graph databases connectable and queryable.

In the proposed system, the first step depends on different methodologies following the variety of information carriers and to the availability of specific applications and tools. In our experiments, we relied on Revit DBLink application for the extraction of data from models and Dynamo for extraction of specific datasets (Simeone, 2017), while for other information carriers, such as reports or calculation notes, we con-

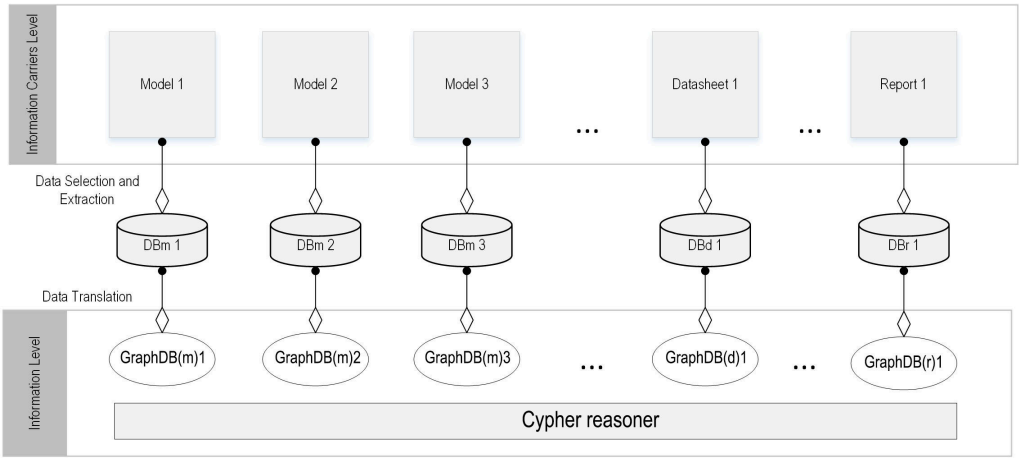


Figure 1
The proposed new CDEs schema composed of the Information Carriers level and the Information Level.

sidered useful using synthesis datasheets linked to actual documents. Because of the wide number of information stored, this extraction activity is coupled with a filtering feature that selects only specific data required by the information level. Although this process could be potentially applied to all information formalized, limiting the amount of information formalized is functional to the necessity of having a lean system to ensure qualitative coherence of information while delegating more strict and accurate data coherence and consistency verification (i.e. clash detection) to other applications outside the Common Data Environment. The second passage is instead based on the re-organization of the extracted and selected data in a Common graph database that ensures information to be formalized in a way to allow check, comparison, validation among different datasets (Fig.1).

Each model template requires a specific translation method depending on the BIM authoring tool and its database structure. This aspect only partially hinders the process because of the simplicity of the translation methods and their re-usability in similar AEC processes. This two steps process translates information heterogeneously provided in different information carriers into a single, homogenous knowledge base, hence allowing reasoning operations as well as information comparison and general coherence checking. The use of common representation standards, such as the use of IFC owl template (Pauwels, 2015), and agreed formalization methodologies, such as schedules templates and synthesis data structures, deeply affects efficiency and speed of the process. To operate on the Information Level, a Cypher-based reasoner has been integrated into the proposed system. The reasoner allows users to develop and execute reasoning queries to verify and compare data stored in the information level. For instance, it allows verifying if the number of spans of a bridge as design in a BIM model is coherent with the data stored in its calculation report, alerting the design team in case of incoherencies and discrepancies. Specific sets of reasoning rules can be used for specific features of the design to be checked directly in the CDE, improving actors' awareness of the state of the information shared in the collaboration platform.

## THE IMPLEMENTATION OF THE INFORMATION LEVEL THROUGH GRAPH DATABASES

To manage, query and capitalize the data introduced in the CDE by different information carriers, this research developed the information level relying on the use of the graph database technology, implemented through the Neo4J platform (Francis, 2018). In this way, it is possible to have a homogenous way of formalization of information extracted from or connected to the different models provided. Each model provides a set of information that can be organized in a network of entities, relationships, and properties that can be retrieved and used in simple or complex queries. In the case of BIM models, usually organized through the family->type->instance structure, the graph databases nodes are the instances of the model (the ones usually defined by an ID in the models, such as a specific pillar, a column, etc.) while the labels provide the family/type classification. Relationships among nodes represent the constraints and the link between entities in the BIM Model, such as a floor constrained to a specific level (fig. 2 and fig. 3).

In the case of other models, such as planning schedules, Quantity Take Off models, or 4D models, it is usually possible to directly access to modelling entities (i.e. tasks, take off items, etc.) and their connecting relationships, recreating graph databases. A bit more difficult is the extraction of data from other information carriers such as reports, etc. In that case, it is necessary to have at least the relevant data sets to translate them in a different data graph. At first, the graph databases elaborated from the different models reside in the information level as independent, coherent graphs but, since they are formalized homogeneously, it is possible to construct queries and algorithms to 1) run across in a transversal direction between different graphs, 2) access and verify the information and, if conditions are verified, generate new relationships between nodes/entities in different graphs. For instance, if the same building component (i.e. a beam) is represented in different models and there is a way to recognize the correspondence (such as the same ID, or the reference to the same structural grid point) it is possible to create a relationship corresponding to and start connecting the two graphs.

Figure 2
A portion of the tested graph database that shows entities (nodes) and relationships. Labels represent family/type classes as per usual BIM elements schema.

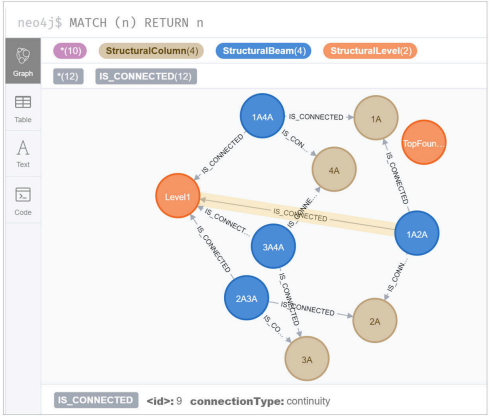


Figure 3
The same portion of the graph database in fig.2, expressed as a table to show the formalization of properties of entities as extracted by the BIM models.

| "n" |
| --- |
| {"xPosition":5.5,"xDimension":0.5,"yPosition":0.0,"yDimension":0.7,"Height":3.0,"reinforcementRate":270,"gridReference":"3A","id":1573,"information_source":"StrModel_054"} |
| {"xPosition":0.0,"xDimension":0.5,"yPosition":0.0,"yDimension":0.7,"Height":3.0,"reinforcementRate":270,"gridReference":"4A","id":1574,"information_source":"StrModel_054"} |
| {"xDimension":0.3,"Length":5.5,"Height":1,"id":1600,"reinforcementRate":240,"gridReference":"2A3A","information_source":"StrModel_054"} |
| {"xPosition":5.5,"xDimension":0.5,"yPosition":6.0,"yDimension":0.7,"Height":3.0,"reinforcementRate":270,"gridReference":"1A","id":1572,"information_source":"StrModel_054"} |
| {"xPosition":0.0,"xDimension":0.5,"yPosition":6.0,"yDimension":0.7,"Height":3.0,"reinforcementRate":270,"gridReference":"2A","id":1571,"information_source":"StrModel_054"} |
| {"xDimension":0.3,"Length":5.5,"Height":0.7,"reinforcementRate":240,"gridReference":"1A2A","id":1601,"information_source":"StrModel_054"} |
| {"xDimension":0.3,"Length":6.0,"Height":1,"id":1602,"reinforcementRate":240,"gridReference":"1A4A","information_source":"StrModel_054"} |
| {"xDimension":0.3,"Length":6.0,"Height":0.8,"reinforcementRate":240,"gridReference":"3A4A","id":1603,"information_source":"StrModel_054"} |
| {"Elevation":3.0,"LevelDef":"Level1","id":"L01"} |
| {"Elevation":0.0,"LevelDef":"TopFoundation","id":"L02"} |

```
neo4j$ MATCH (x:StructuralBeam), (y:StructuralColumn) where (x.gridReference
       contains y.gridReference) and (x.information_source =
       y.information_source) CREATE (x)-
       [r:IS_CONNECTED{connectionType:'continuity'}]→(y) RETURN x, y, r
```

Figure 4
An example of a constructed query in Cypher language, that retrieves structural elements ("MATCH" part) and generates new relationships based on the structural grid ("CREATE" part).

For this research, we decided to rely on the use of Cypher, a declarative query language that enables both queries and data formalization, specifically designed to operate in graph databases environment and interact with nodes, relationships, properties, and patterns. In this proposed evolution of CDEs, the creation and control of 'horizontal queries' between graph databases represent a new task in the current AEC information management processes, that can impact the current role of the project information manager. In this task, the set of queries necessary to connect different data models stored in the CDE is project-dependent because it has to be tailored in accordance to the scope of each model, the formalization structure of its data, and the objectives of the query itself. If compared to other query languages (i.e. the SWRL - Semantic Web Rule Language), Cypher supports this process of queries set customization using its syntax based on natural language and its very linear logic. As in the example shown in figure 4, the use of keywords such as MATCH and CREATE allows structuring complex queries to recognize patterns in the graph databases and generate new data, providing a query template that can be adapted to similar necessities in other projects. The development and refining of query sets for AEC projects is an open topic that can introduce a new standardization level in the current practice.

For data extraction from BIM Models, and their connection to the graph databases in the information level, different solutions can be conceived relying on approaches and tools already available in the AEC sector. In the case of Autodesk Revit models, we utilized two different methodologies that rely on the use of the Revit DBLink and the use of Dynamo algorithms for data extraction in tables. We found the DBLink approach useful in the case of necessity of a bulk translation in a graph of the entire model, although some issues arise in terms of manageability and conversion from the relational database to the graph one. The use of dynamo scripts, instead, allows for a selective extraction that can be tailored following the query necessities of each project. Both these methods provide a bidirectional connection between the models and the dataset elaborated in the CDE information level. Current Visual programming approaches are a relevant contribution to this process, allowing to select, filter, and export datasets in formats such as .csv that allow graph databases editor to access data and automatically reconstruct the network of entities. Another opportunity, at present only available in the exporting direction, is represented by the use of the IFC schema. In this case, the use of the IFC-OWL ontology (Pauwels, 2015) is a reference for the implementation of standardized procedures for its conversion in a graph database, and the construction of queries accessing the IFC data (fig. 5).

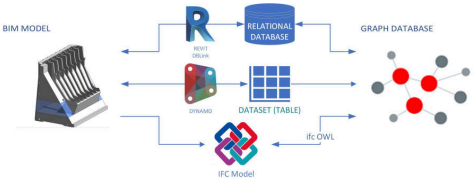


Figure 5
Interoperability between BIM Models and Graph databases in the CDE Information Level, based on different data exchange methodologies (RDMS, Dynamo, IFC schema).

## POTENTIALS AND OPEN PROBLEMS OF GRAPH DATABASES APPROACH TO COMMON DATA ENVIRONMENTS

In our experiments on the adoption of graph databases as a new way of formalizing and make available information in AEC Common Data Environments, some potentials and limits have emerged, not specifically related to technical aspects but rather to the introduction of this approach within already consolidated workflows and protocols. The processes described in this paper underlay the more general information management protocols and practices that drive current AEC projects, essentially dealing with how to formalize information and knowledge. From an end-user perspective, it is not possible to define a unique workflow but we rather suggest that some additional actions have to be carried out, while shar-

ing documents and models, to favour the development of a coherent and efficient Single Source of Truth as necessary in AEC projects. The data translation from models - or other information carriers - to graph databases is an activity not yet considered in current AEC collaboration processes, that requires efforts, competencies and time, especially if performed cyclically as in architectural design. Heterogeneity of models is a hindering factor that requires the development of customized algorithms and protocols for data extraction, impacting the adoption of this new approach to the entire project dataset. Another obstacle is represented to the necessity of new figures in the process, able to manage and query this new CDEs: the graphs themselves can easily become too complex, and database experience is, therefore, necessary to control that complexity and ensure efficacy in data retrieval. At the same time, we assessed relevant improvements on the quality, consistency and coherence of the information formalized through graph databases, as well as in its understanding by the different actors involved in the process. Simplified interfaces, for instance, allow the actors to explore the data graphs reaching the needed information and being supported in its interpretation by visualizing the connected information. We also noticed that the effectiveness of this approach is higher if not applied to the single elements that compose the building but rather operating at a higher level of representation where decisions are made on systems and general aspects of the building, while highly detailed, discipline-specific issues are usually more manageable through dedicated tools. This approach also provides a relevant improvement in terms of queries capabilities: horizontal queries allow to move across the different data formalized in the different models, while the Cypher language allows to perform also complex systems of queries and to elaborate a higher level of semantics, usually not accessible by direct operations on the single models.

## CONCLUSIONS AND FUTURE PROSPECTS

The research described in this paper aims at enhancing the current Common Data Environment for BIM-oriented processes, by integrating the CDE repository structure with a knowledge-based system, developed through graph databases. Its scope is to extend CDEs usual repository function with the possibility to perform qualitative checking and evaluation of the data stored in the different models and information carriers, immediately detecting potential incoherence and improve design integration. The conceptual framework of the presented system relies on a semi-automated process of data extraction, selection and translation into a homogeneous set of graph databases that allows reasoning operation and data accessibility. As shown by first tests in simulated AEC processes, the proposed system is potentially able to enhance the efficacy of a crucial element of BIM processes - the Common Data Environment - by transforming it from a repository of not-coherent documentation to an integrated data environment oriented to actual collaboration. Also, the introduction of CDE information level developed through graph databases allows for enhanced flexibility in terms of queries and verifications that can be performed by connecting and moving across different models datasets, without constraining the users to rely only on pre-defined metadata controls as in current CDEs. The presented approach, although still explorative, opens the research to further developments and even integration with other research streams that could be beneficial for the entire sector. In particular, research is still needed to make the entire workflow more efficient by reducing the variability of stored data and the re-usability of queries. The use of ontology-based schemas such the IFC-OWL could ensure a better homogeneity of the formalized data and, at the same time, allowing for a standardized library of queries. Another aspect, not often discussed in our field, is related to the integration of information sources different from models, that are currently attached as external documents: further research should focus on re-thinking such way of com-

municating a project, formalizing information with different technologies and ensuring automation in data elaboration. Another research step to be considered is the use of machine learning techniques for queries and data retrieval, further enhancing the efficacy of the system. To conclude, in the scope of current research AEC processes research, this work contributes to the current quest for a new generation of collaborative digital environments, able not only to make data and information accessible but also to integrated them, ensuring their coherence and their comprehension to all the actors involved in the process.

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# From the Cognitive to the Sentient Building

## *Machine Learning for the preservation of museum collections in historical architecture*

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*The aim of this paper is to evaluate the efficacy of the Digital Twin approach to achieving Sentient buildings able to develop preservation and conservation action plans from environmental data. The case study is based on the integration of an H-BIM model with an AI-based Decision Support System implementing Machine Learning techniques for conserving museum collections in historical buildings.*

**Keywords:** *Digital Twin, Historical Architecture, Artificial Intelligence, Decision Support System, Museum Collections, Preventive Conservation*

### INTRODUCTION

The relationship between humans and machines has evolved considerably in recent decades with the introduction of various technologies, especially Artificial Intelligence (AI), which has become prevalent in a range of applications, including Architecture Engineering Construction Operation (AECO). One of the main objectives in AECO is to develop semi-automatic workflows that can minimize some of the more mundane and time-consuming activities associated with preservation, leaving professionals to focus on higher added-value activities. Heritage buildings that host museum collections can gain the most from these technologies because heritage preservation relates to the conservation of the building, or container, and to the appropriate environmental conditions for the housed collections, or the content. The study deals with the experimentation of innovative and advanced preservation methodologies for museum collections in historical buildings through the development of a DSS (Decision Support System) that uses ML (Machine Learning) to implement effective conservation strategies. We investigate the DT (Digital Twin) approach to promote a Cognitive building to the Sentient status able to perceive external inputs and develop optimal preservation and conservation solutions.

The new HS - BIM (Historical Sentient - Building Information System) methodology for historical building documentation, management, and conservation is proposed in our case study involving the MuRa university museum (Museo della Rappresentazione), in villa Zingali Tetto, Catania. This historical building constructed in 1930 houses a collection of engravings and design drawings by architects and etchers. The experimentation focuses on the thermo-hygrometric conditions for the preventive conservation of the collection and the museum rooms.

The HS-BIM is defined after a review of the state-of-the-art and of the specific problem to solve, followed by an illustration of the relative methodology applied directly to our MuRa case study. We conclude with some reflections regarding the adopted

methodology as well as anticipated future developments.

## BACKGROUND AND PROBLEM DEFINITION

The growing impact of Industry 4.0 on AECO is driving continuous experimentation and innovation in industry and manufacturing, which is in turn manifesting in new building construction and indoor environments. In recent decades, AECO has focused heavily on Energy Management through the integration of intelligent technologies in building systems (Wong et al. 2005). The concept of Building Automation System has evolved from Automated Buildings able to monitor key performance indicators, to Smart Buildings able to analyze energy consumption (Clements-Croome 2004), to Cognitive Buildings capable of learning behavior (Ploennigs and Schumann 2017). Indeed, sensing technologies, distributed intelligence and IoT (internet of things) are integral to the CB (Cognitive Building) concept and its strict association with the notion of DT (Digital Twin), which Bolton et al defines DT as "a dynamic virtual representation of a physical object or system across its lifecycle, using real-time data to enable understanding, learning and reasoning" (Bolton et al. 2018; p. 783). DT has found application in different fields and has achieved various levels of maturity Since Michael Grieves first coined the term in 2002 for manufacturing contexts (Grieves 2019). Today, the integration of AI with IoT and BIM (Building Information Modeling) technologies (Pasini et al. 2016) allow DT to assimilate, analyze, simulate, predict, prescribe and act with minimal human involvement, as envisioned by Bien et al (Bien et al. 2002; Zuchker et al. 2018).

In literature, we find several attempts to define the DT maturity level in terms of sophistication. The definition by Madni et al (Madni et al. 2018) is generally associated with the industry sector: Level 1 or Pre-Digital Twin, virtual system model with an emphasis on technology/technical-risk mitigation; Level 2 or Digital Twin, virtual system model of the physical twin exists; Level 3 or Adaptive Digital Twin, virtual system model of the physical twin with adaptive UI; Level 4 or Intelligent Digital Twin, virtual system model of the physical twin with adaptive UI and reinforcement learning. Simon Evans [2] proposes six levels or Built environments: Level 0 or Reality capture, such as point cloud, drones, photogrammetry, or drawings/sketches; Level 1 or 2D map/system or 3D model, such as object-based data with no metadata or BIM; Level 2 or Connect model to persistent (static) data, metadata and BIM Stage 2, such as documents, drawings, asset management systems; Level 3 or Enrich with real-time data, such as from IoT and sensors; Level 4 or Two-way data integration and interaction; Level 5 or Autonomous operations and maintenance. To date, these concepts have found limited application in historical heritage and museum domains, even if the Natural History Museum in London has recently embraced this technology [1].

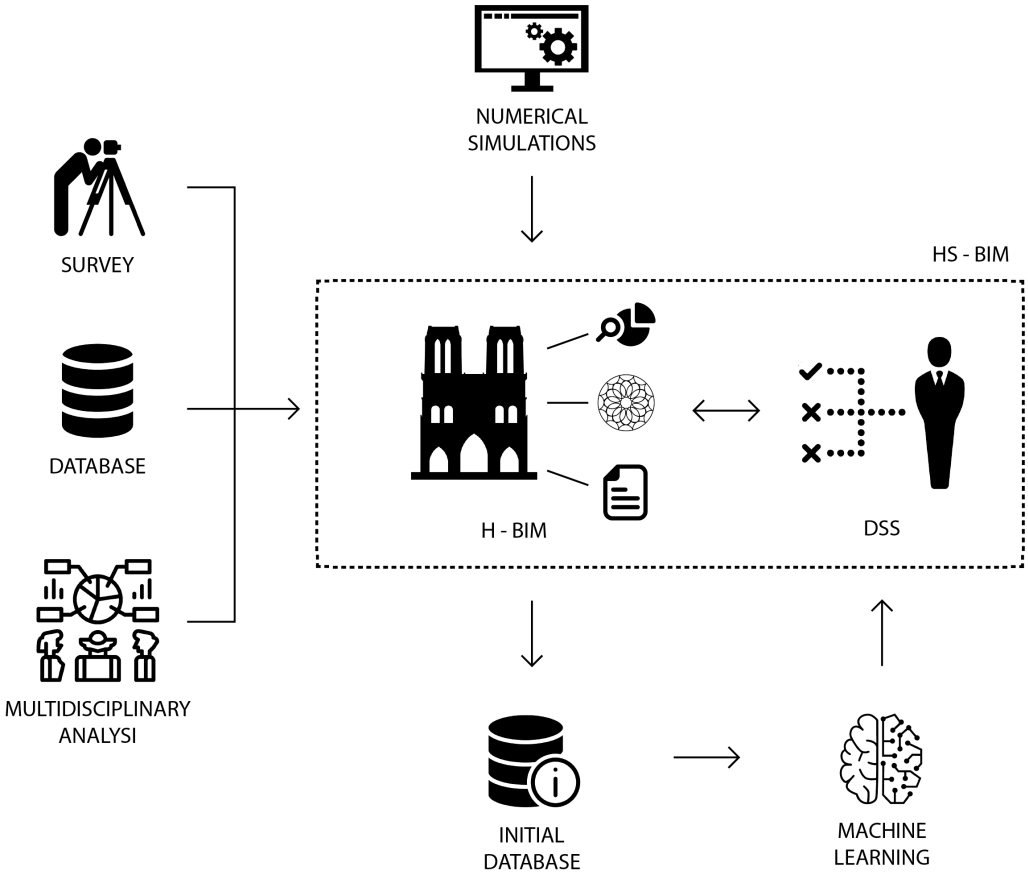
Many institutions have applied H-BIM (Historical Building Information Modeling), which has been accompanied by improved computation techniques in architecture thanks to the development of user-friendly VPLs (Visual Programming Language) such as Grasshopper, Dynamo, Node-Red, Ardublock, NET-Lab Toolkit, ReactiveBlocks, GraspIO, and Wyliodrin. These tools provide the flexibility to enrich H-BIM models with new concepts, definitions, layers of actions and knowledge, as well as to manage, catalog and reorder the data and the different relationships contained in the models (Argiolas et al. 2015; Giovannini 2017; Tono et al. 2019). DSS is being increasingly applied in the management of historical buildings with museum functions, often in conjunction with WSNs (Wireless Sensor Network) for constant and real-time monitoring of all the relevant parameters required by museum configurations inside broader architectural frameworks. Remarkable examples of such installations include the Sala dei Cinquecento at Palazzo Vecchio in Florence (Viani 2014), the Palazzo della Civiltà Italiana in Rome (Trento et al. 2019) and the Museo Egizio in Turin (Calvano et al. 2020).

ML applications in Architecture and Construction were already being developed for the first CAD

applications in the 1960s (Wright Steenson 2017), experimenting with direct human-computer interaction to facilitate, optimize and develop the design process. There are several cases in which neural networks have been trained for design purposes in the construction sector, including the work carried out at the University College of London to examine the possibility of training a robotic arm to perform woodwork (Brugnaro and Hanna 2017).

The global objective is to therefore develop a system for evaluating the rooms of a building using datasets made from the assessments of users in many other buildings, to understand which recurring patterns ensure conditions of comfort (Davis 2016; Kim 2018). Some research has also gone into the classification of different types of environments using neural networks (Tono et al. 2019; Peng et al. 2017).

Figure 1
HS-BIM Workflow.



## HS-BIM

The HS-BIM (Historical Sentient - Building Information Modeling) definition proposed for this research draws on DT maturity levels relative to historical building preservation, with the aim of achieving H-BIM model performance level 5 'Autonomous operations and maintenance' [2] and level 4 'Intelligent Digital Twin' (Madni et al. 2019) through the application of AI techniques, specifically ML. We therefore define HS-BIM (La Russa 2019) as a BIM model that can perceive the external and internal inputs of the historical building it represents, identify and report signs of degradation, and implement learning mechanisms to generate appropriate preservation strategies from the input data **(fig. 1)**.

The paradigm shift resides in the relationship between the historical building and the professional figures who deal with its management, conservation and architectural restoration. The well-established analogy between a human being and a building in conservation and architectural restoration circles involves the interpretation of architecture as a living organism that progresses through a life cycle in certain states of health that may require remedial therapy (Marconi 1993). It is possible to identify similarities between the physical and behavioral aspects of living beings and the techniques used in BIM-based methodologies [3]. If we consider the diagnostic sensors that provide real-time data from strategic points in a building as a peripheral nervous system, we can cast our medical analogy by likening the structure of the building to a corpus, with its animus or nervous system represented by a virtual prosthetic H-BIM model.

Despite its apparent complexity, it is still primarily a passive model until DSS based on Machine Learning mechanisms can render the DT or HS-BIM model sentient. Effective learning experiences for the HS-BIM are obtained through supervised training scenarios controlled by the designer.

According to the psychologist Thorndike (Thorndike 1905), learning in sentient beings generally occurs through the transfer of knowledge from adult individuals, or is embedded in the nature of the being. The initial training dataset therefore represents the adult teacher that helps build the anima of the sentient HS-BIM model in its evolution from a passive to an active decision-making model.

## METHODOLOGY

The methodology addresses the management of the thermo-hygrometric conditions for the preventive conservation of museum collections in buildings with high historical value. After an initial step aimed at the 3D digitalization of the building and semantic modeling in a BIM environment, we proceed with the development of a DSS capable of making appropriate suggestions related to the conservation of the museum collections and architectural interior spaces. A VPL development environment is used to build the DSS and embed the ML logic that can accept a training dataset and consequently recognize the impact of various actions on thermo-hygrometric conditions in order to elaborate appropriate solutions. The methodology is structured as follows:

- 3D digitalization of the historical building through laser scanning and photogrammetric survey, and critical analysis of the construction apparatus of the historical building;
- H-BIM modeling of the whole building, taking into account high LOD for museum rooms under analysis;
- gathering of meteorological data stored by the nearest climate station;
- microclimate analysis of the urban context;
- simplification of the H-BIM model into a NURBS model and thermo-technical information enrichment in VPL environment;
- setting out existing action strategies regarding the maintenance of museum collections;
- specification of the applicable thermo-hygrometric norms for the conservation of the collections in each museum room;
- gathering of the thermo-technical data collected inside the museum or, if unavailable, creating a synthetic dataset for energy simulations

Figure 2
Views of villa Zingali Tetto: a) exterior; b) winter garden made by Salvatore Gregorietti (Palermo 1870 - Palermo 1952).

based on the conservation strategies already in use;
- data labeling and filtering to ensure supervised learning of the training dataset;
- training and validation of the ML algorithm.

## CASE STUDY

The methodology was validated on a cultural heritage building subject to complex preservation requirements: villa Zingali Tetto in Catania **(fig. 2)**. Built in 1930, the structure houses the Museo della Rappresentazione (Museum of Representation) managed by the Department of Civil Engineering and Architecture of the University of Catania (La Russa 2019a).

Geometric and spatial surveys of the villa, undertaken predominately with laser scanners and photogrammetry, were complemented with archival research surrounding its construction and history. Its complex interior arrangement required as many as 233 TLS (Terrestrial Laser Scanning) scans to develop an idea of the space syntax and expositions in the many small rooms, corridors, and staircases on each floor of the villa **(fig. 3)**. SFM (Structure from Motion) techniques were used to acquire several decorated wood surfaces, ceiling frescos, and pieces of furniture to further structure subsequent energy simulations.

Figure 3
View of the point cloud.

Due to the high cultural importance of the villa, any conservation strategy regarding appropriate thermo-hygrometric conditions for the collections should not be invasive and would therefore be restricted to passive techniques (natural ventilation, occupation of the rooms) and optimized management of existing HVAC (Heating, Ventilation and Air Conditioning) systems.

Machine Learning (ML) algorithms based on various linear regression formulas, often used to forecast trends in finance, meteorological models and others (Bakar et al. 2009; Eck 2017; Abbas 2017), were

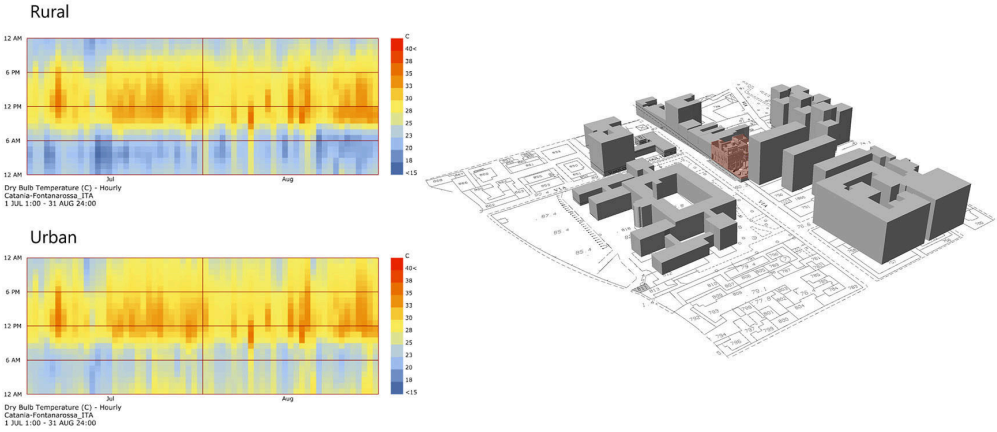



Figure 4
Urban heat island analysis based on data acquired from the closest rural weather station and urban scenario around the villa: On the left, a comparison between rural and urban (derived by Dragonfly processing) meteorological data that shows the effects of the heat island; on the right, the villa Zingali Tetto (in red) in a 3D context.

adapted to the specific DSS system design requirements for our case study in order to deliver a digital model able to offer analysis of the relationship between input variables and output results. Unfortunately, the initial dataset used to train the ML algorithms would normally require direct measurement data of the museum environments over at least one calendar year, together with candidate use strategies to help the ML system derive conclusions from the results.

Energy simulations can, however, be used to build synthetic datasets for the initial learning phase in lieu of real sensor network data. We used the Rhinoceros 6 modelling environment to develop energy simulations integrated with Grasshopper and the Dragonfly and Honeybee plugins. To calibrate our simulations, we used Dragonfly **(fig. 4)** to adapt meteorological data from the closest rural weather station to generate an urban heat map around the villa, using the resulting data to configure the functional parameters of the simulations conducted on a simplified 3D model of the villa using the Honeybee plug-in **(fig. 5)**.

The analysis was performed in the dining room with wooden furniture, the stained-glass sunroom winter garden and the two adjacent rooms housing prints and drawings **(fig. 6)** and **(fig. 7)**, with the relevant thermo-hygrometric parameters according to normative guidelines (Manoli 2015) listed in Table 1 **(tab. 1)**.

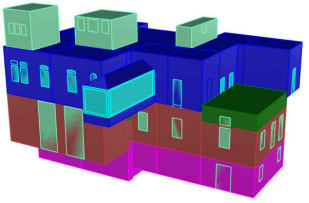


Figure 5
The simplified three-dimensional model of the villa for energy simulation.

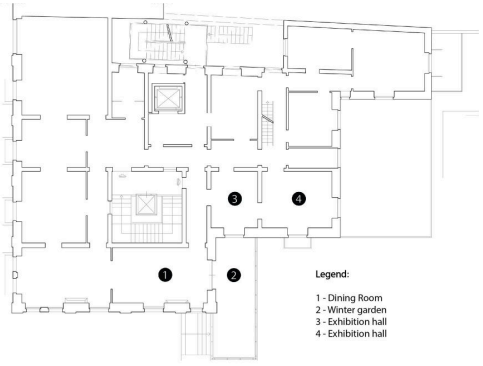



Figure 6
Environments analyzed by DSS.

Specific combinations of parameters are defined

Table 1
Thermo-hygrometric parameters required in relation to the specific room.

| Room | T (°C) | $U_r$ (%) |
|---|---|---|
| Winter garden | DT < 5 | < 45 |
| Dining room | 19 - 24 | 40 - 65 |
| Exhibition rooms | 19 - 21 | 50 - 60 |

for each of the passive strategies involving natural ventilation, visitor limitation and the HVAC system, and the data from thermo-hygrometric conditions simulations are stored and labelled, excluding any daily average data where the thermo-hygrometric parameters are only satisfied in a single room. The labeled dataset is then fed into the DSS developed in Grasshopper to generate the environmental dry bulb temperature and relative humidity parameters, as well as the following usage configurations denoted by keys and variants:

```
Adopted solutions = {0 : 1st variant;
 ↪ 1 : 2nd variant; 2 : 3rd variant}
```

The order in which they appear corresponds to the different fields of application (first line: occupation, second line: ventilation, third line: air conditioning system), and the dataset assembled in this way can only contain successful cases (supervised learning). The Grasshopper plugin LunchBoxML that provides support for the multivariate linear regression component has been used to identify the correlations between the assumed usage configurations and the satisfaction of the environmental parameters for each day. The ML algorithm in the Grasshopper component develops a linear association between the temperature and relative humidity input data

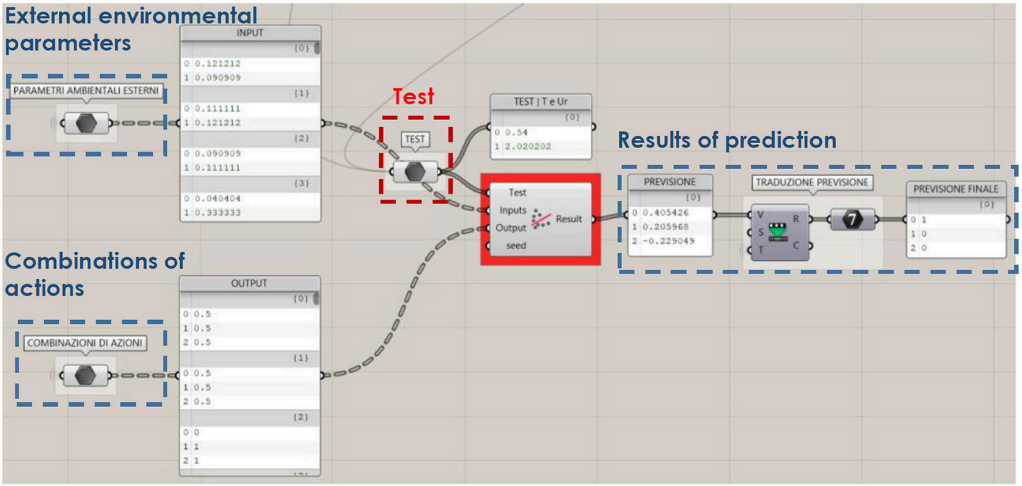
Figure 7
Room selected for thermo-hygrometric analysis: a) Winter garden; b) Dining room; c) Exhibition hall.

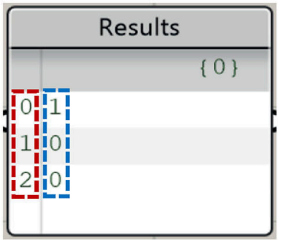
and the configuration output data. A user can therefore generate a possible usage strategy for any day by entering the relevant temperature and humidity inputs for that day, and thereby obtain the most probable use configuration that would be appropriate for the given environmental parameters **(fig. 8)**.

## CONCLUSIONS

This study has investigated the notion of DT in relation to the preservation of museum collections in historical architecture, defining an HS-BIM model that integrates AI, BIM and IoT technologies. We also tested a workflow using a simulated dataset that would effectively bypass the onerous task of gathering the minimum data necessary for training the decision-making model, and at the same time remove potentially prohibitive costs associated with sensor installation and setup. The workflow therefore promises to ensure continuity in preventive conservation activities in the absence of qualified professionals, or monitoring systems, or both.

In this first testing stage, we applied the multivariate linear regression ML algorithm to manage the combination of external climatic condition inputs




| Index | Actions | 0 | 1 | 2 |
|---|---|---|---|---|
| 0 | Occupancy (# visitors) | 27 | 22 | 17 |
| 1 | Natural air ventilation (# hours) | 2 | 4 | 6 |
| 2 | Air conditioning (# hours) | 2 | 4 | 6 |

Figure 8
DSS code in Grasshopper and results of the simulation. In this example, with an outdoor temperature of 40 °C and a relative humidity of 0.54, the DSS suggests the combination of actions { 1; 0; 0 } which equates to allowing access to only 22 visitors, using natural ventilation for 2 hours, and 2 hours of a specific air conditioning setting.

and potential internal prevention strategies. Future research will focus on generalizing the algorithm and accommodating a wider range of input and output parameters.

Assuming that at this stage of the research we have achieved DT maturity level 3 according to the definition by Evans [2], we shall also pursue level 5 maturity through the possible implementation of Artificial Intelligence mechanisms such as Deep Learning to allow the transition to a learning system involving attempts and errors.

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# Algorithmic Framework for Correlation Between Microclimate Control and Space Usage in Outdoor Public Spaces

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*Effects of extreme temperatures are the cause of health-related problems and have an impact on how we go about with our daily lives. This study addresses the critical question on the relationship between architecture and climate. It probes into the correlation between urban environments and microclimate while focusing on the outdoor public spaces. This paper provides a conceptual framework for information processing to enable spatiotemporal design strategies for outdoor public spaces. The flow of information starts with data gathered by sensors, relies on the computational techniques for processing and ends with information as specific as instruction for the behaviour of spray nozzles emitting water vapour. The contribution of this paper is the advancement of the design methodology of public spaces, through the development of dynamic design strategies based on the ability to sense climatic conditions in localised areas and map behaviour of occupants in real-time.*

**Keywords:** *Interactive Architecture, Responsive Environment, Evaporative Cooling, Microclimate, Outdoor Public Space*

## INTRODUCTION

The global climate is changing, and heat waves are becoming more frequent. Extreme temperatures are the cause of health-related problems and have an impact on our daily lives. WHO (2019) identifies heat as one of the leading threats to sustainable development. It says that the effect is most pronounced in cities characterised by large expanses of urban paved and concrete structures, which absorb radiant heat, and conversely, a lack of reflective or green spaces to effect cooling. It warns that average centre city temperatures are anywhere from 3-5$^{o}$ C above those in the surrounding countryside. A large amount of heat generated from urban structures, as they consume and re-radiate solar radiations, and from the anthropogenic heat are the leading causes of Urban Heat Island (UHI) effect (Memon 2008). The problem of heat accumulation in urban areas drives the sizable body of research (e.g. Dwivedi 2019; Taha 1997). UHI is now recognised as the most evident characteristic of urban climate, with an influence on material and energy flows in cities, and therefore their structure and function (Yang et al. 2016).

Known UHI mitigation techniques include the use of adequate materials, urban vegetation, water and shading as potential solutions to moderate tem-

peratures and increase the adaptive capacity of cities to the warming climate (Osmond and Sharifi 2017). However, the existing body of knowledge on adapting to the UHI effect is not fully assimilated into architecture and urban design (Yow 2007). And, despite the evolving understanding of urban climates changes, the use of innovative technology to augment architectural solutions is still insufficiently integrated in practice (Lally 2012; Yang 2012).

The study reported on in this paper, explores the potentials of dynamic architecture enabled by responsive technologies. In the book "Interactive Architecture" Fox and Kemp (2009, p 27) write that "there is a great potential for dynamic architecture that arises from understanding what space or object is currently doing and how it can aid in promoting or accommodating a specific task. Some of this understanding relates to dynamically changing architectural elements or spatial layouts that address desires to have public or private space, to optimise thermal, visual, lighting, and acoustic conditions, and to promote sharing or collaboration in space. This understanding boils down to examining how architecture can extend the notion of enhancing our every day activities by assisting users in accomplishing specific activities or possibly suggesting new ways to interact with space and other users to complete tasks."

This paper focuses on the role of evaporative cooling, one of the water-based solutions for UHI mitigation. Evaporative cooling removes heat from the atmosphere as water changes phase from liquid to vapour. The ambient air temperature is reduced by forcing water through small nozzles under high pressure, producing clouds of fine mist which absorb ambient heat to be evaporated in the air (Osmond and Sharifi 2017). The system is effective while it has low power demand and thus is responsible for light carbon dioxide emission (Farnham et al. 2017; Frederick and Khosla 2014).

We recognise the potency of evaporative systems to control outside air temperature, but also their potential to improve occupants' engagement with space. Two precedents demonstrate a successful application of evaporative cooling in the architecture of outdoor public spaces. Tanner Fountain at Harvard University, USA (1984) by PWP Landscape Architecture and Le Miroir d'eau, Bordeaux, France (2004) by Michel Corajoud both utilise water emitted from nozzles to alter microlite in public spaces in response to the weather. PWP states that the Tanner fountain invites human participation without suggesting any particular activity and that it is heavily used by people of various ages who sit, read, climb, jump, flirt, converse, and meditate (1984). Same applies to the project in Bordeaux, and both schemes exemplify the potency of evaporative cooling and microclimate control in architectural design.

The conceptual framework presented in this paper focuses on the expanded role of an evaporative cooling system in outdoor public spaces. The study is drawn on the research efforts which integrate science, professional practice, and stakeholder participation to improve the design of public spaces (Ahern et al. 2014); and whereby technology is used to mediate between disciplines and to enable participation of end-users (Felson and Pickett 2005; Hanzl 2007; van Den Berg and van Winden 2017; Yigitcanlar et al. 2008).

Systems affecting thermal comfort are amongst the most studied and developed technologies related to the built environment (e.g. Hatefnia and Ghobad 2015). However, in outdoor spaces, they are seldomly optimised according to measurements which go beyond climatic conditions, such as measurements of occupants' behaviour (Zhe et al. 2019). The similar view is established in earlier research (Nikolopoulou, Baker and Steemers, 2001; Spagnolo and De Dear, 2003) but to date, the issue remains understudied. In the past decades, there has been considerable interest in developing innovative ways of measuring the built environment, covering diverse topics such as those related to bus stop crime (Loukaitou-Sideris 2001) and residential satisfaction in mass housing projects (Dinc 2014). Such measurements offer themselves as a design intelligence and the basis for dynamic (spatiotemporal) concep-

tions of the built environment. Increasingly, efforts are being made to use remote sensing technology and numerical simulation methods, to study ecological and environmental effects of UHI across different scales (Tsou et al. 2006; Munitxa and Bogosian 2015; Voogt and Oke 2003; Yang et al. 2016) and for the mapping of microclimates (Zellweger et al. 2019). To this end, a wide array of techniques to measure specific aspects of space use has been tested, based on energy consumption, C02 emission, movement detection, sound levels, radio-frequency identification (RFID) and many more (Stojanovic and Vujovic, 2020). However, occupancy data is proved to be elusive and difficult to establish with sufficient accuracy (Sun et al. 2020). A growing number of studies demonstrate that measuring devices of different types should be employed simultaneously to avoid inaccuracies (Hobson et al. 2019). This study examines the use of pressure-based sensors integrated into the floor surface instead of commonly used cameras or PIR sensors. It is assumed that pressure sensors will provide more consistent space coverage, will avoid occlusion between users, and will not intrude privacy. The reliance on tactile sensors for information harvesting leads to the use of less demanding recognition algorithms based on weight or gait. (Bränzel et al. 2013).

## OBJECTIVE

This paper provides answers to how responsive technologies can optimise evaporative cooling solutions to mitigate UHI effects in outdoor public areas, as well as support occupants' engagement with space; and how to formulate dynamic design strategies for better correspondence between microclimate control and space usage

The ability to sense climatic conditions in localised areas and map behaviour of occupants in real-time allows designers to employ active strategies. However, current practice shows a lack of coordination between climate control and outdoor space usage. This paper provides a tool for information processing to enable spatiotemporal design strategies for outdoor public spaces. The information flow starts with data gathered by sensory devices, relies on the computational techniques for processing and ends with information as specific as instruction for the behaviour of spray nozzles emitting water vapour.

This study aims to create a conceptual framework for dynamic architecture, which integrates the operation of the evaporative cooling system and occupants' behaviour, with the help of responsive technologies. We assume that technology is not only improving microclimate conditions but also changing the way people interact with space. In response to the topic of the eCAADe 2020 conference, Architecture and Fabrication in the Cognizant Age, this paper presents a novel conceptual framework for correlation between human activities and climatic conditions. The objective is to provide grounding future studies through the implementation of advanced computation methods and make a contribution to the development of the design methodology of outdoor public spaces.

## ALGORITHMIC FRAMEWORK

The method presented in the following paragraphs focuses on the algorithmic framework for data harvesting, information processing and actuation of spatial change. The conceptual framework integrates climate control and activities of occupants to enable dynamic design strategies for outdoor public spaces. The concept is based on the ability to sense selected climatic conditions in localised areas and map behaviour of occupants in real-time. The proposed framework offers two critical advantages. Firstly, it provides a way to optimise cooling systems in outdoor areas, by their selective and intelligent application. Secondly, the framework contributes to the design methodology of public spaces by providing designers instantaneously with information otherwise available only through post-occupancy evaluation. The proposed design approach is user-centred and allows for user behaviour to influence the climate

conditions in the built environment via operation of a responsive system.

In evaporative cooling, the combined effect of water pressure and restriction delivered by the nozzle affects the size of the droplet issued into the environment. An increase of either pressure or restriction results in the smaller size of the droplet, which evaporates more quickly. However, a study on evaporative cooling (Nunes et al. 2011), points out that numerical fluid analysis (Yamada et al. 2008) show that there is no significant temperature reduction for different particle sizes issued from the nozzles, and suggests that water vapour release periods and distribution patterns may have a more significant impact on the efficiency of the system. Therefore, this study explores how to establish a more accurate control of release periods and distribution patterns with the use of innovative technologies. The output information on release periods is calculated as the duration of action and pause time while information on distribution patterns is delivered as a percentage of active nozzles as well as the angle at the top of spray dispersal cone.

## DATA HARVESTING

This paragraph introduces the network of sensors needed to harvest data and a scheme for integrated measuring of parameters related to meteorological conditions and occupants' behaviour (Figure 1). There are two categories of input information, the first one is for climatic conditions and the second one is for occupants' activities. Climate conditions are established through localised measurement of solar irradiance, wind speed and direction, temperature, and humidity. Occupants' activities are observed as presence, movement, and interaction or distance between people. The scope of activities measured is based on the categorisation of activities in outdoor public spaces established by Jan Gehl (1985). In the seminal book "Life Between Buildings: Using Public Space" Gehl writes how outdoor activities are influenced by climatic or physical conditions and how design affects the possibility of meeting, seeing and hearing other people in outdoor public spaces. He identifies essential activities in outdoor public spaces as walking, standing, sitting and places specific importance on the interaction between people.

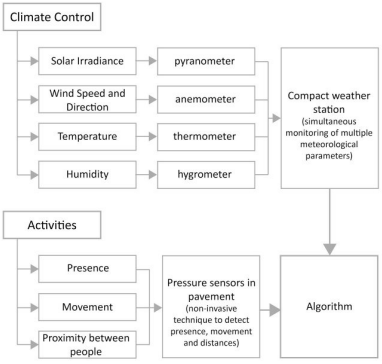



Figure 1
Integrated measuring of climate conditions and occupants' activities

Sensory devices employed for the measurement of climatic conditions are anemometer, thermometer, and hygrometer. Multiple sensors are linked into clusters to form a compact weather monitoring station allowing for simultaneous recording of key meteorological parameters.

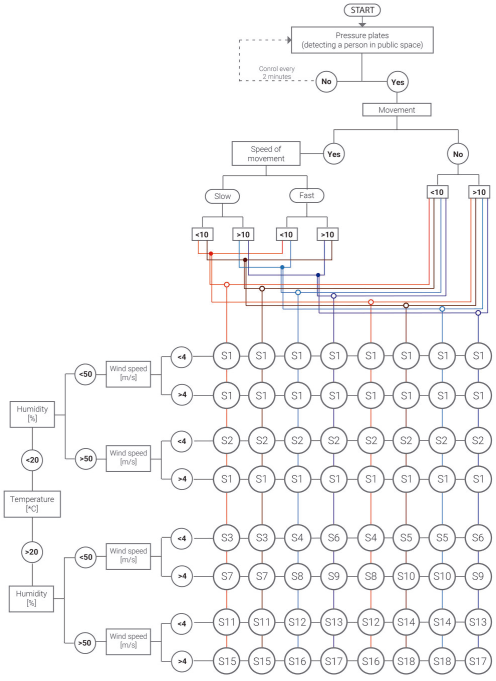
Devices for measurement and the subsequent establishment of activity categories according to the method introduced by Gehl (1985) are pressure sensors located on the pavement surface. A vast amount of pressure sensors is employed rather than cameras in order to protect the privacy of occupants. A non-invasive technique is given an advantage over a visual recording to minimise data-privacy concerns and provide easier delivery. A pressure sensor detects the presence of an occupant, upon which the speed of movement and distance between users is established. According to Gehl (1985), the speed of the movement is proportional to the engagement between people and the built environment. If people move more quickly, they are about to commute from one place to another, but if they move more slowly or stop this is because they are attracted to engage with space, and they are willing to interact with other people. Accordingly, presented measuring ap-

proach supplies information needed for the evaluation of the existing outdoor public spaces, which is useful for future design. In this study, integrated measurements of climate conditions and occupants' activities are fed to the algorithmic framework and processed to produce output information needed for the autonomous adjustment of climatic conditions.

## INFORMATION PROCESSING

This chapter outlines an algorithmic structuring of the information flow. Two categories of information, introduced in the previous chapter, are structured into vertical and horizontal input in the diagram (Figure 2).

Figure 2
Algorithmic framework




Vertical input is provided by tactile sensors. Pressure plates embedded in the paving surface detect the presence of people in the outdoor public space. Based on this information, the speed of movement and proximity between occupants is established. This reliable and robust system is composed of square tiles, each equipped with a certain number of pressure sensors (usually four strain gauge load cells), processors, and a wired connection to the neighbouring cells (Andries et al. 2015). Depending on the resolution of the slabs, the proposed system can distinguish standing from walking, as well as to measure steps and therefore provide sufficient information on occupant's activities. Simultaneously, horizontal input is provided by the localised weather station. Horizontal input categories are limited for this paper to include temperature, humidity, and wind speed.

The algorithm results in a matrix, showing possible scenarios. Each of 64 possible combinations in that matrix requires activation of the cooling system in a slightly different way. While it is understood that the ability of the system to act with the minimal waste of energy is essential, it is also assumed that insignificant differences between regimes allow for the very similar or identical application of the cooling system. It is, therefore, accepted that a limited number of modes would be sufficient for the operation of the proposed system.

In this study, the microclimate control is delivered through evaporative cooling, an effective and energy-efficient system, composed of the water pump, filter, supply tubing and different nozzles. The evaporative cooling system reduces the ambient air temperature, with the use of water. Through nozzles and under high pressure, water is sprayed into the air to produce clouds of fine mist. The mixing between water and the air stream cools the ambient air from its dry-bulb temperature to its wet-bulb temperature. Evaporative cooling systems are capable of reducing outdoor temperature between 3 and 8 ˚C, depending on the relative humidity. They are most effective if the relative humidity is low.

## ACTUATION OF SPATIAL CHANGE

The actuation of the presented framework is based on the performance of nozzles. The proposed cooling system allows for their selective and clustered employment. The cooling water mist is sprayed in selected zones only, where climatic conditions and occupant's presence are requiring so. There are three categories of output information regulating nozzle performance, and they are water vapour release periods, number of active nozzles, and the spray dispersal angle.

The first category, water vapour release periods are expressed in minutes. It defines the duration of nozzle action as well as the pause periods. The second category, the number of active nozzles, is captured as a percentage of nozzles which are active, out of all nozzles belonging to the same system. It is anticipated that the climate of outdoor public space will be controlled by multiple systems, each composed of 10 nozzles and assigned to specific microclimatic zones. Within any one outdoor public space, there could be one or many such systems at work. Finally, the spray dispersal angle is controlled by the intensity of air pressure and is expressed in degrees of the angle at which water mist is dispersed through the nozzle. Nozzles use air to break up the fluid into a spray pattern. The maximum dispersal angle is 70˚, and each source installed at the recommended height of 3m may affect the area measuring up to 5m in diameter (Osmond and Sharifi 2017).

A wide variety of nozzle types are currently available and used in different industries for the emission of both gases and fluids. Different types enable different distribution patterns and provide an opportunity for a responsive application of the cooling system. Two or more nozzles, located at the same spot, may be employed in alternation to optimise the performance of the system. The number of active nozzles and the spray angle definition have a critical impact on the rate at which water mist evaporates and thus influences the efficiency of the cooling system. The effectiveness of the proposed system is improved with its ability to respond to fluctuations in temperature, ambient humidity and wind speed. At the same time, presented the algorithmic framework along with the integrated measuring approach also enables the system's response to occupants' activities. For example, when people congregate in specific areas, more nozzles are activated. If the ambient humidity is low, more nozzles are activated for longer periods of time and at short intervals. If the outside air temperature is low, a smaller percentage of nozzles are activated and for shorter periods with longer pauses. If wind speed picks up, the spray angle is reduced, even if the temperature does not drop. The table below provides descriptive information of the system's response according to 6 representative modes established through the integrated measuring of climatic conditions and occupants' activities (Table 1).

| | INPUT: integrated measuring of climatic conditions and occupants' activities | Water vapour release periods (min) | Active nozzles (% of all nozzles) | Spray dispersal angle (°) |
|---|---|---|---|---|
| Mode 1 | any number of people walking slowly, any number of people walking fast, any number of people not moving, temperature lower than 20°C, when humidity is less than 50% with any wind speed | Off | n/a | n/a |
| Mode 2 | any number of people walking slowly, any number of people walking fast, any number of people not moving, temperature lower than 20°C, when humidity is more than 50% and wind speed less than 4m/s | On (1 min, every 30 min) | 20% | 70° |
| Mode 3 | less than 10 people walking slowly, any number of people walking fast, less than 10 people not moving, temperature higher than 20°C, humidity less than 50%, wind speed less than 4m/s | On (2 min, every 2 min) | 50% | 70° |
| Mode 7 | less than 10 people walking slowly, any number of people walking fast, less than 10 people not moving, temperature higher than 20°C, humidity less than 50%, wind speed more than 4m/s | On (2 min, every 5 min) | 50% | 50° |
| Mode 11 | less than 10 people walking slowly, any number of people walking fast, less than 10 people not moving, temperature higher than 20°C, humidity more than 50%, wind speed less than 4m/s | On (1 min, every 10 min) | 20% | 35° |
| Mode 15 | less than 10 people walking slowly, any number of people walking fast, less than 10 people not moving, temperature higher than 20°C, humidity more than 50%, wind speed more than 4m/s | On (1 min, every 20 min) | 20% | 15° |

Table 1
Representative input modes and output information

## DISCUSSION AND CONCLUSIONS

The presented conceptual framework provides grounding for the application of advanced computational techniques and further interdisciplinary collaboration between architecture, computer science and mechatronics. The framework utilises algorithmic logic to allow synchronous measuring of climatic

conditions and occupants activities and relies on the use of responsive technologies to establish a two-way relationship between occupants' behaviour and physical conditions of the built environment. In this study, the actuation of spatial changes is delivered by an evaporative cooling system. The release periods and water misting patterns delivered by selectively activated nozzles are brought into relation with meteorological conditions and human behaviour in outdoor public spaces.

The study, motivated by rapidly changing climatic conditions in urban areas, addresses the lack of architectural use of innovative technologies identified in the literature review. The presented approach reflects on the complexities of the relationship between the built environment and the climate and establishes a way to integrate innovative technologies into architecture. The research report shows how the application of responsive technologies could help optimise cooling solutions in public areas, as well as help occupants to engage with space. The algorithmic logic applied provides an open-end structure and a scalable design tool that can be applied in different environments and adjusted to diverse input information.

The presented framework is a generic solution, necessitating adaptation according to specific physical, geographical and seasonal conditions. The adaptation aspect is not included in the scope of this report. Further development of the proposed framework is planned in a laboratory setting through research based on prototyping and iterative testing of the concept. At this stage, the research is presented at the conceptual level to structure further development.

The presented framework is beneficial to architects and urban designers by enabling better correlation between microclimate control and space usage in outdoor public spaces. The benefits are twofold. The proposed framework improves the efficiency of the evaporative cooling system, while also providing means for architects to design space as dynamic and changing according to occupants needs and climatic conditions. An effective outdoor cooling system will improve the user comfort in public spaces, while the responsive change of physical conditions enhances occupants' engagement with space. The approach envisages a dynamic transformation of microclimatic zones within outdoor public spaces and allows the user to take an active role in the process.

The presented framework also enables evidence-based understanding of how public spaces are being used in different weather conditions. It allows for real-time data collection and structuring of data sets according to specific questions raised by designers. In the form of instant and continuing post-occupancy evaluation, such acquisition of information may be a valuable addition to design knowledge. Future study will focus on the actual data capture and creation of useful data sets.

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# D2.T9.S2. CULTURE /SHIFT THROUGH UBIQUITOUS COMPUTING/SCRIPTING AND LINGUA FRANCA

# It's Art Baby

## *The Science of Comparing and Scoring Artistic Endeavour at Schools of Higher Education*

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*Scientific output has well-established methods for comparing and scoring the quality and quantity of the work. For artistic output this matter is not settled at all and a subject of much debate. We present a method which has been developed in Czech republic since 2011. This method is used to compare and score the artistic output of all schools of arts in the country (for example, music, performative arts, architecture, literature, sculpture, painting). The system presented in this paper is based on the Saaty-method (also known as Analytic Hierarchy Process). After almost eight years of development and use, the system has proven as a valuable asset to assess in an objective way output between many different forms of artistic works. In 2016 the system was incorporated in the Higher Education Act. In the paper we present a brief history of the development and the principles of AHP applied in the system. In particular, we will focus on the findings in architecture derived from the system. Finally, we will discuss possible implications for architectural education in general.*

**Keywords:** *Register of Artistic Performance, SAATY method*

## INTRODUCTION

In this paper we present a method which has been developed in Czech republic since 2011. This method is used to compare and score the artistic output of all schools of arts in the country (for example, music, performative arts, architecture, literature, sculpture, painting) (Stoklasa et al. 2016). Early attempt to create such a system was made in Slovenia by the University of Slovenia, however, this did not lead to an operative system. Norway has a system called Khioda, and Slovak republic has it's system CREUČ - it has to be noted however, that both systems only *record* artistic output, but do not *score* it. The scoring is a vital part since this is where comparative judgements need to be made.

The system presented in this paper is based on the Saaty-method (also known as Analytic Hierarchy Process) (Saaty 2013). To support the process an online system has been developed, which uses Fuzzy Logic (Zadeh 1975; Sugeno and Yasukawa 1993). The system is called *Registr uměleckých výstupů* (RUV) - which translates into *Register of Artistic Performances*

(RAP). The administrative process is organised as follows. Schools enter their results (works of art) in the system, usually done per individual. A school main supervisor checks and filters the results. The dean of the school has to approve the selection that will continue in the system. A department from the Ministry of Education then prepares the data, on which two assessors are appointed for each entry. Uniformly judged entries proceed further, while for entries with varying assessments the main supervisor gives the final degree. Based on the comparison, then the final board of the system assigns the scores. Categories are established on three main parameters: (A) Relevance and Importance; (B) Range and size; and (C) Institutional context. After the comparison scores are given to the works.

After almost eight years of development and use, the system has proven to be a valuable asset to assess in an objective way output between many different forms of artistic output. In 2016 the system was incorporated in the Higher Education Act. In the paper we present a brief history of the development and the principles of AHP applied in the system. In particular, we will focus on the findings in architecture derived from the system. Finally, we will discuss possible implications for architectural education in general.

## PROBLEM OF ASSESSING ARTISTIC OUTPUT

Scientific output has well-established methods for comparing and scoring the quality and quantity of the work. For artistic output this matter is not settled at all and a subject of much debate. In fact, quite a few people would argue that art cannot be objectively judged at all. This leads to a rather strange situation at institutions of higher education, especially those involved with artistic endeavor. Those schools have a scientific and artistic aspect to them. From students and tutors alike, it is expected that they deliver high quality work. On a regular basis, the quality of the student work is judged through their delivered work. This work forms a considerable portion of all their efforts at the school. Yet, although all this is done on an almost daily basis, an objective way for such assessment is missing. When we consider the artistic and scientific output of the staff of the schools, then we must note that whereas the scientific part has fairly well-set criteria for assessment, the scoring of artistic output in most cases does not have this. When comparing between schools of art, the situation becomes even more complicated.

## CALL FOR AN OBJECTIVE SYSTEM OF ARTISTIC ASSESSMENT

The first president of Czechoslovakia, Tomáš Garrigue Masaryk, wrote: *"The work of art is an echo of a special cognition of the world and I say further it is as independent and just as cognition as scientific."* (Masaryk,T.G. 1926) This sentence was an inspiration at the beginning of the project of the Register of Artistic Performances. Most of the teaching staff of art schools are active artists with enormous artistic creative potential, which is an important inspiration for students. It has already been said: artistic creative activity is equal to scientific work. So how to evaluate the creative potential of art schools or art programs? This problem started to appear at art schools during the doctoral programs discussions. Scientific activities at art schools were usually devoted to the study of history, theoretical analysis, and philosophical treatises. All of these have their established methodologies and output channels that are more or less traditionally scientific. Creative works, such as poetry, buildings, sculptures, musical compositions, and so on do not have such mechanisms. Yet we can see that the creative activity is essential in both scientific research and artistic creation. There is a constant balancing between creative scientific and artistic invention. At the beginning of the Register of Artistic Performance project there was a clearly declared will between all partners for communication, cooperation, and a friendly mutual understanding. It was recognised by all that the scientific or artistic creative process is worthy of admiration and moves mankind towards positive development. Thanks to the Bologna Declaration, the teaching system has begun to change and

separate academic institutions have moved to three-level structured studies. A three-tier structure system has allowed mobility within the European area. The Bologna Declaration called for a single credit system and also focused on qualification frameworks. The question arose: how to measure the quality of art education at art colleges?

## CONCISE DEVELOPMENT OF REGISTER OF ARTISTIC PERFORMANCE (RUV) SYSTEM

A *Registr uměleckých výstupů* (RUV) Working Group has been established from the Commission for Art Schools at the Higher Education Council. The Higher Education Council, which represents all higher education institutions in the Czech Republic, is an advisory body to the Ministry of Education. The RUV Working Group convinced the plenum of the Higher Education Council and received support for the pilot development project. The development project was carried out by representatives of the most important art schools and art faculties in Czech Republic. The task was to create a system of registration of teachers' artistic output and subsequent rating or evaluation. Inspiration was provided by a registration of scientific works similar to the Register of Artistic Performance, with the project researchers wanting to avoid evident shortcomings in the scientific evaluation. Participants of the development project were people of different Arts disciplines and had to agree on a joint solution. Seven artistic segments were created: Architecture; Audio-vision; Design; Music; Literature; Scenic arts; and Arts. In the individual segments - Arts disciplines, a group of teachers was formed from Arts schools and Arts faculties, where they teach one of the disciplines. For each segment, a so-called Segment Board was established. Each Segment Board was headed by the Segment Supervisor. In addition to the segments, a very important analytical unit was created, with fellow mathematicians.

At the start of the project, the participants of the development project prepared a set of teacher´s potential artistic outputs over the past 3 years. In this way, they obtained a sample that had to be categorized. As soon as the structure of the Register of Artistic Performance was clear, work began on the RUV Application, where data on individual outputs - works and performances of individual academic staff - were collected. A multi-level certification process has been set up. In order to establish wide consensus between all schools involved, a very important role was put on public relations. A total of 7 RUV publications were produced, that explained the system for all involved. In 2012, an International RUV Conference was held at Czech Technical University, Faculty of Architecture. Supervisors and members of Segment Boards visited individual art colleges in the Czech Republic and consulted RUV with other teachers. The RUV system was constantly analyzed. Individual Segment requirements were compared with other Segments. Everyone held in mind that the RUV should be an open system, but the terms of reference had to be clearly defined. The result of several years of work was a functional RUV Application, where every year teachers of art schools register their new art outputs and then this data is submitted to the certification process. At the end of the process, each output receives a three-digit code that corresponds to the appropriate score. The RUV system has been adopted in the Higher Education Act since 2019. Arts colleges have obligation to register the art outputs of teachers in the Register of Artistic Performance. The result of the certification - score evaluation - is one of the quality indicators of the given Arts school.

Table 1
The different outputs in each segment.

| Architecture | Audio-vision | Design | Music | Literature | Scenic arts | Arts |
|---|---|---|---|---|---|---|
| Realization | Cinematic Architecture | Realized design | Dramaturgy | Essay | Play | Installation of artwork |
| Project, design | Dramaturgy | Unrealized design | Music and sound direction | Comics | Radio recording | Design of artwork |
| Zoning plan | Actor performance | Exhibition design | Musical performance | Memoirs | Dance productions | Realization of a new work of art |
| Regulatory plan | Production | | Interpretation, performance | Novel | Text bases | Restoration activities |
| Competition design | Camera | | Composition | Translation | | |
| Exhibition of architectural works | Costumes | | | Collection of poems | | |
| | Make-up | | | Set of song lyrics | | |
| | Script | | | | | |
| | Direction | | | | | |
| | Writer | | | | | |
| | Sound Track | | | | | |

## ADMINISTRATIVE METHOD OF RUV

Any academic who has passed official selection procedure as a teacher at art college, faculty of art, or teaches an art subject (for example at a faculty of education) has the opportunity to submit his(her) art output to the Register of Artistic Performance (RUV). Depending on the nature of the art the teacher lectures, (S)he writes his(her) outputs into the RUV application according to the instructions of the relevant segment. The following table 1 gives a brief overview of the different outputs in each segment. After a long public debate, each segment determined what outputs - works or performances - would be accepted at RUV.

A team of mathematicians led by doc. Talašová prepared a mathematical model for three-criteria evaluation of individual works of art. Categorization by impact and **importance**, scaled in levels ABC (and non-scored category D), categorization by **size**, scaled in levels KLM, and categorization by **institutional context**, scaled in levels XYZ (see table 2). The categorizations thus produced a total of 27 (using the non-scored category D 36) combinations. The individual faculties involved in the project tried to classify individual works and performances on a limited number of outputs according to 7 segments and 27 categories first.

**Application and its data.** The team developed the RUV application at Czech Technical University in the Development and Information Center. First of all they needed to define the necessary data. Thanks to already closed collections for 2008, 2009 and 2010, it was possible to clearly define the basic structure of inserting outputs into the application. It was necessary to unify the nomenclature across the segments and to identify areas where the differences showed up. In these areas, individual segments created extensive lists - so-called code lists, where it was possible to select options according to a specific output in a particular segment. After that the selection could be categorized for each individual output according to already mentioned categories - *importance*, *size*, and *institutional context*. Our task was to unify the requirements of individual segments. It was necessary to create a clear framework of application for the commissioning of artistic outputs ranging from architectural realizations, through the work of filmmakers, concerts and theater performances, literary essays to works of art and design work. It was imperative that the labeling should not become too complicated or overly refined. It was necessary to create a real simple-looking application that would enable the administration of the Register of Artistic Performance and the entire certification process and would provide important data on the creative quality of art school teachers and faculties.

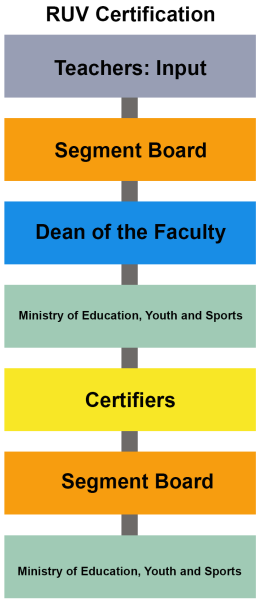
To instruct people how to work with the RUV application, the so-called RUV manual was created, and is publicly accessible on the website of the Ministry of Education, Youth and Sports. The manual provides 36 (27 points) options for including output, with scores ranging from **maximum value** *AKX* to **minimum value** *DMZ*. The Relevance and Importance or Originality categories are determined by the depositor himself according to the recommendation

| | | | |
|---|---|---|---|
| **Relevance and Importance or Originality** | **A** | new work of art or artistic performance | **of fundamental importance and originality** |
| | **B** | new work of art or artistic performance | **bringing a number of major innovations** |
| | **C** | new work of art or artistic performance | **developing current trends** |
| | **D** | new work of art or artistic performance | **containing development potential (not scored)** |
| **Size** | **K** | new work of art or artistic performance | **large range** |
| | **L** | new work of art or artistic performance | **medium range** |
| | **M** | new work of art or artistic performance | **small** |
| **Institutional Context** | **X** | new work of art or artistic performance | **international context** |
| | **Y** | new work of art or artistic performance | **national context** |
| | **Z** | new work of art or artistic performance | **regional context** |

Table 2
The basic categorization is the same for all segments. Each output is assigned by a 3-letter code.

Figure 1
RUV certification scheme

of the certain segment. To assist the deposit, general definitions of individual categories were developed and specific examples are available for comparison. The Scope - Size category is specified in each segment according to the nature of each output and is binding for depositors. Information is always given in the updated segment manual before collection. The Institutional Context category is clearly identified in the so-called *INDICATIONS* and *REPORTS*. After the completion of the faculty entry, the Segment Board is responsible for checking the factual correctness of the assignment according to the segment manual and recommending changes in the impact and significance category. The Segment Board's task is to compare outputs (A, B, C, D) across faculties. An important moment is the recommendation to reduce the amount of outputs A. Entries that are truly worthy of score A need to be excellent and absolutely unquestionable in the art community. Segment boards can thus point to possible upward and downward fluctuations in the self-assessment of individual depositors. An important role in the whole process is played by the Dean of the Faculty, who responds to any disagreement of the segment supervisor (the result of comparative assessment across faculties for a whole range of segments will appear for each output in the application). This is followed by a certification process where each output is judged by pairs of independent certifiers, who are experts in their art field. They have input data of the depositor's output, and the stated opinions of the segment supervisors and the Deans of the faculties. After the certifiers are done, the majority agreement process takes place. If the majority agreement can not be reached, a controversial situation arises and the judgment of a third expert is used. The process results in certified outputs (see figure 1).




## SAATY METHOD FOR ASSESSING ARTISTIC OUTPUT

We cite here the original text concerning the method of certification from the article Register of artistic performances and evaluation of results of creative activities, by Talašová, Stoklasa, and Holeček (2012): *"The initial classification of works of art into individual categories of RUV is suggested by the applicant; the correctness is then verified by a committee composed of renowned personalities of individual segments of artistic production (so-called certifiers). The scores for individual categories of artworks were determined by the Saaty method. The principle of this method is repeated measurement of the relative significance of these categories via expertly defined preferences intensities between them (the preferences intensities between categories were defined by a team composed of guarantees of individual segments of artistic creation). Resulting scores of categories range from 8 to 305 points for one*

*accounted output - as well as scoring of the most substantial part of Research & Development results (publications in impact journals).*"

The Saaty method was taken as the basis for scoring of all 27 scored categories of works of art (see table 3). This method is currently considered to be the most appropriate mathematical tool in general for determining relative evaluations of arbitrary objects based on expertly expressed preferences intensities. Its advantage is, on one hand, that experts have the opportunity to express their preferences verbally by choosing from a predetermined set of language terms. On the other hand, the advantage of this mathematical method is its thorough theoretical foundation, which includes: **a.** Method of assigning point scores to language terms; **b.** The idea of repeated "measurements" of the relative significance of objects by gradually comparing all objects in a set with each of its elements; and **c.** Algorithm for calculating the resulting relative evaluations. Much effort has been devoted to determining how to best translate the experts' preferences regarding the 27 scored categories of artworks (illustrated for each art segment by specific examples) into a mathematical model used to calculate their scores (Zelinský 2012b, RUV3, p. 47).

| Indication | Relevance and Importance or Originality | Size | Institutional Context | Self Vector Method | Geometric Mean Method |
|---|---|---|---|---|---|
| AKX | fundamental importance and originality | large | international | 305 | 305 |
| AKY | fundamental importance and originality | large | national | 259 | 254 |
| AKZ | fundamental importance and originality | large | regional | 210 | 217 |
| ALX | fundamental importance and originality | medium | international | 191 | 194 |
| AMX | fundamental importance and originality | small | international | 174 | 171 |
| ALY | fundamental importance and originality | medium | national | 138 | 138 |
| ALZ | fundamental importance and originality | medium | regional | 127 | 124 |
| BKX | bringing a number of major innovations | large | international | 117 | 112 |
| AMY | fundamental importance and originality | small | national | 97 | 94 |
| AMZ | fundamental importance and originality | small | regional | 90 | 87 |
| BKY | bringing a number of major innovations | large | national | 79 | 75 |
| BKZ | bringing a number of major innovations | large | regional | 66 | 66 |
| BLX | bringing a number of major innovations | medium | international | 62 | 61 |
| BMX | bringing a number of major innovations | small | international | 48 | 50 |
| BLY | bringing a number of major innovations | medium | national | 44 | 46 |
| BLZ | bringing a number of major innovations | medium | regional | 40 | 41 |
| BMY | bringing a number of major innovations | small | national | 37 | 38 |
| BMZ | bringing a number of major innovations | small | regional | 31 | 30 |
| CKX | developing current trends | large | international | 26 | 26 |
| CLX | developing current trends | medium | international | 24 | 24 |
| CKY | developing current trends | large | national | 19 | 20 |
| CKZ | developing current trends | large | regional | 17 | 18 |
| CMX | developing current trends | small | international | 16 | 16 |
| CLY | developing current trends | medium | national | 12 | 13 |
| CLZ | developing current trends | medium | national | 10 | 11 |
| CMZ | developing current trends | small | regional | 9 | 9 |
| CMZ | developing current trends | small | regional | 8 | 9 |

Table 3
Categories of scoring.

## EXPERIENCES WITH THE RATING SYSTEM

In the following sections, we briefly discuss experiences with the rating system.

**Excellence in RUV.** The determination what counts as excellency in RUV constitutes a cornerstone of the working method. The basic RUV credo for excellence has been the magic number 2% for outputs marked with the letter A. It means, that in the total number of outputs in a certain segment there should be only 2% considered A - Excellent. In the long run, this principle proves very useful. Outputs A are always a grateful topic. Every year, the best results are assessed in the Segment Boards. The rating of A to B is drastically reduced at the meetings of the Segment Boards. Outputs marked A are to be the prestige of every school. It constitutes output that would be showcased on the home web page as the best PR asset.

**Pictorial documentation.** During the first collections of outputs (2008-2010), Excel spreadsheets provided links to websites where information on the output could be obtained. In the Architecture segment, photographs from the realization or visualization of competition projects (projects) were included. They best documented the author's artistic intention together with an accurate annotation. The problem was with the instability of external websites. To counter this, for example, at the Faculty of Architecture in Brno, a web page of pedagogical projects for the needs of RUV was established. The RUV Application offered the possibility to place a maximum of 5 jpg or pdf files. For architects these attachments were mandatory. Other Arts segments did not initially use visual documentation. This measure was primarily intended to help certifiers, but gradually became important for system transparency and comparison of outputs. Additional segments have been added, and now image documentation is mandatory for all depositors - for example recording photos from events or invitation documentation are being uploaded to the system.

**Team authorship.** Works (architectural constructions, projects, musical works, and so on) and performances (interpretation, rendition of film or theater

role, direction, and so on) are submitted in RUV. Performances are attributed to one artist, but works often have multiple authors. The Architecture segment has long drawn attention to the question of team authorship. For architects, it became apparent that on the given work - the realization or project of the house, more than half of the outputs were applied by team authorship. Teamwork, however, disadvantages architects and projects into a divided number of points for one output. Each year an analysis of certified outputs is carried out and the analytical team submits to all supervisors of each segment a comparison: the number of outputs in individual segments, at individual schools, the number of registered outputs per artist, and so on. If there are some cases of extraordinary increase or decrease in the individual monitored categories, then the rules for insertion are adjusted, but always in agreement of all of the segments. As an example, I will give a long-term balance of the number of individual outputs in the ABCD categories. **Category A**: new work of fundamental importance and originality (about 2%); **Category B**: new work bringing a number of significant innovations (about 30%); **Category C**: new work developing current trends (about 60%); **Category D**: new work containing development potential (not scored) (about 8%). This is the distribution of ABCD outputs in all segments from 2012 to 2019.

## DISCUSSION OF ARCHITECTURAL OUTPUT

Outputs in the architecture segment are mainly realized constructions, whereas other outputs are mostly projects. Certain visionary projects we can only see as ideas of the future. Competition projects have their complications - sometimes a winning design is realized, but sometimes another participant in the competition gets to realize their design, and sometimes the competitors are unlucky because none of the ideas raised by the competition are realized. Additionally, architects will spend a lot of time in various stages of project documentation. To build a house means to overcome a considerable number of obstacles. It is not always possible and the project ends prematurely. If the project continues to realization, it is not always possible to realize the author's project without significant modifications. For these reasons, the project is a fully-fledged output in the architecture segment and it is up to the depositor to select the project from the project documentations. The project, which fulfilled the requirements for the project documentation for the building permit, was therefore presented to the public. It has the possibility to be applied in the Register of Artistic Performance. The last possible output in the architecture segment are exhibitions of architectural works of the architect. The RUV application offers very interesting information. Architects are more dependent on the economic situation than other types of art. As the economy goes up, it is starting to flourish in both private and state investment in construction. In the following graph, the total numbers of outputs in the architecture segment and the numbers of individual types of outputs - projects, realizations and exhibitions show the growth of outputs in general and the dynamics of growth of individual activities (see figure 2).

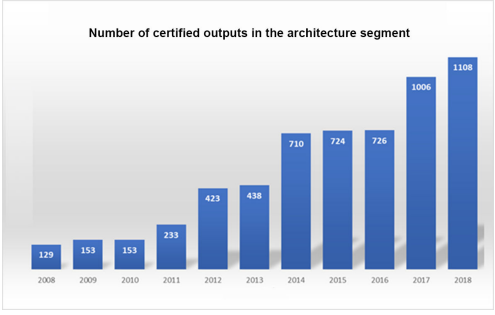



Figure 2
Output growth in the architecture segment

## IMPLICATIONS FOR ARCHITECTURAL EDUCATION

Through the years of experience with RUV, it is without doubt that the Register of Artistic Performance has been very important for Faculties of Architecture. We can draw the following conclusions:

1. Architecture is art.
2. Creation of an objective system of registration and evaluation.
3. An objective system of output registration that aids in further quality evaluation - for example in habilitation procedure, or doctoral study assessment.
4. Comparison of the level of teachers at faculties of architecture.
5. Comparison of the level of teachers at faculties of architecture with the level of teachers at other art colleges.
6. Indicator of level of cooperation of the university with practice.
7. Interconnection of art schools.
8. Data source as one of the source materials for the school development strategy.
9. Significant financial benefits in the budget from the Ministry of Education.

**Recommendations and wishes for RUV at faculties of architecture.** Long-term cooperation with other art schools has shown that architecture and architects have a deficit in promoting their excellent media outcomes compared to other areas of art. Nowadays the situation is improving, but it is necessary to admit to theaters, musicians, filmmakers, designers and artists their achievements are a fixed part of a media space. Architecture is far behind. It turns out that the number of teachers at faculties of architecture is not negligible. The faculty management is increasingly interested in employing excellent architects to teach students. This would bring schools and faculties of architecture closer to the usual practice at prestigious universities in the world.

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# From Analysis to Design

## *A framework for developing synthetic shape grammars*

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*This paper focuses on the problem of lack of housing, due to fast urbanization processes and urban population growth, particularly in developing regions of the globe. The goal is to propose an alternative for planning housing settlements, using a computational-based approach, and having as a case study an existing Brazilian favela, Santa Marta. The paper proposes a strategy to bridge between the use of shape grammars from analysis to design, by performing changes on the rule level. The research includes the development of an analytical grammar that captures the physical features of the settlement and its subsequent transformation into a synthetic grammar that can generate urban configurations that keep key features of the original settlement while avoiding its flaws. The paper is focused on the grammatical transformations performed to the analytic grammar to obtain the synthetic grammar and its subsequent validation. Results show that the solutions generated by the synthetic grammar do have higher quality when compared to the case study. This strategy is proposed as a framework for the application of shape grammars in design.*

**Keywords:** *shape grammars, grammatical transformations, Santa Marta favela, Santa Marta Urban Grammar*

## INTRODUCTION

This paper is part of a larger research that explores the use of digital technologies to overcome the lack of housing due to population growth and fast urbanization processes, particularly in developing regions. The goal is to propose a computational approach to the planning of housing settlements, based on the case of Brazilian informal settlements. Technology was used to (1) map, analyze, and explain the morphology of informal settlements and (2) to develop an alternative methodology to plan housing settlements that present qualities valued in informal settlements but not their flaws.

The research encompasses the following steps: (1) analyze the existing settlement by constructing different models of representation; (2) infer an analytic shape grammar; (3) assess the quality of the existing settlement using an established evaluation system; (4) change the analytic grammar to improve urban quality, thereby creating a synthetic shape grammar and; (5) validate the synthetic grammar by evaluating the quality of its outcomes. This paper focus

on steps four and five and it shows the grammatical transformations performed to the analytic grammar to obtain the synthetic grammar and its subsequent validation.

The Santa Marta favela is the study case used for this research. This informal settlement is located in Rio de Janeiro, Brazil and it has about 4000 residents, living in 1036 buildings. Santa Marta was chosen as the case for this research because it possesses distinct characteristics, such as its prime location within the city fabric (avoiding long commuting of its residents) and the high density of its built environment. The settlement is on a hillside in the south area of the city, close to high-end neighborhoods and touristic attractions such as Christ Redeemer and Sugarloaf Mountain. Several factors help understand why an informal settlement like Santa Marta is located in such a prime area of the city: the steepness of the terrain does not make it attractive for land speculation and social dynamics require a workforce, mainly composed by pink collars and domestic workers, to live close to their jobs in such a high-end neighborhood. The result is a settlement that grows incrementally over time and presents high density, about 2.7 times higher than the average for the city.

To determine the changes that had to be made to the analytical Santa Marta Urban Grammar, the existing settlement was evaluated using an established housing quality assessment system called QUARQ (Pedro 1999a, 1999b, 2001). This system evaluates housing projects at different scales, namely room, dwelling, building, and neighborhood. Santa Marta was evaluated at the neighborhood scale. The evaluation was performed using a software implementing QUARQ. It consists of a questionnaire that is filled in with information on the physical characteristics of the neighborhood, which are then compared to a table with reference values. The result of the evaluation is a score for each of the criteria considered in the assessment - articulation, personalization, pleasantness, safety, and spatial adequacy, and a report with recommendations for improvement. In this paper, we present a summary of the results and the report. More detailed information can be found in Verniz (2020). Previous publications presented the analytical shape grammar, called Santa Marta Urban Grammar (Verniz & Duarte 2017 and Verniz & Duarte 2020). This grammar encodes the settlement process of Santa Marta favela, which is a parametric shape grammar. The grammar account for the definition of building geometries and pedestrian circulation (the settlement is not accessible to vehicles) both in plan and in section.

## THEORETICAL BACKGROUND

Shape grammars were theorized by Stiny & Gips in 1972. They are an algorithmic strategy for analysis and design (Stiny & Gips 1980). A shape grammar is an algorithm composed of an initial shape (that starts the derivation process), a set of rules (that transform shapes), and a vocabulary of shapes (containing all shapes involved during the process of derivation, including the initial shape and the final designs). Labels and weights can aid the derivation process by attribute different characteristics to the shapes (Stiny 1980).

In the years that followed the theorization of shape grammars, several works proposed specific algorithms to describe existing styles in architecture, landscape architecture, and urban planning, such as Palladian Villas (Stiny & Mitchell 1978), Frank Lloyd Wright's prairie houses (Koning & Eizenberg 1981), Mughul gardens (Stiny & Mitchell 1980), and historical Muslim urban quarters (Duarte et al. 2007), to name just a few.

The first work to explore the generative use of shape grammars in an actual design context was the work of Duarte (2001) where he developed a shape grammar for Alvaro Siza's Malagueira's houses with the goal of generating customized houses. Duarte's approach to generative design was a paradigm shift in the use of shape grammars. Although all shape grammars are both analytical and generative (Li 2001), the change of focus in Duarte's work initiated a series of works addressing the generative potential of such algorithms.

In an attempt to describe the evolution of different design styles, Knight (1989) proposed the concept of *grammatical transformations*. According to her theory, changes in different but related styles can be explained by changes in the rules of the underlying shape grammars, such that the grammar of the initial style can be transformed into the grammar of the following style by changing, deleting, or adding rules. By means of such grammatical transformations, the author explained the evolution of Vantongerloo's and Glarner's paintings and the evolution of Frank Lloyd Wright's Prairie houses into Usonian houses, among other cases. The concept of *transformation grammars* was proposed by Eloy & Duarte (2015; 2011) to upgrade Portuguese dwellings from the mid of the 20th century to meet the needs of contemporary households by applying transformation rules to the original layouts to transform them into upgraded layouts. Similarly, Guerritore & Duarte (2018) proposed a transformation grammar to convert a particular type of office buildings into collective housing buildings in Milan, Italy. This type of shape grammar makes changes to already existing built designs. Both concepts, grammatical transformations and transformation grammars show how new design possibilities can be created from more limited initial ones.

In order to classify the use of shape grammars from analysis to design, Knight (2014) identified in the literature four different computational strategies where shape grammars are used to develop new designs. These strategies address the problem in two different ways. The first way is by exploring the design capabilities of the shape grammar (strategy 1). The second way is by performing changes on the rule level (strategy 2) or on the design level (strategies 3 and 4). The first strategy is embedded in every shape grammar, where new designs that fit a specific context can be generated by someone using the grammar. This can be a good strategy to understand a specific style of design or to provide, for example, mass customized products. The second strategy changes the grammar's rule set by changing, deleting or adding rules. Strategies three and four operate on the final design level by acting directly on the generated designs and transforming them into new designs. The difference between strategies three and four lies merely on whether the initial designs were generated by a grammar (strategy three) or not (strategy four), but this difference is not relevant, as it is possible to develop a grammar for the initial design a posteriori and so strategy four becomes similar to three. According to Andrew Li, shape grammars can be classified in two main types, related to their use (2001): analytical shape grammars when there are used to describe existing styles, explaining and replicating existing designs; and synthetic shape grammars when they are used to generate new styles or designs. In the current work, we used strategy 2 to transform an analytical grammar into a shape grammar.

## ASSESSMENT RESULTS OF SANTA MARTA FAVELA

We assessed Santa Marta using an established housing quality evaluation system, to determine what transformations would have to be carried out in Santa Marta's urban grammar to generate higher-quality housing settlements. As mentioned above, QUARQ evaluates housing settlements on four different scales (room, dwelling, building, and neighborhood) and it also classifies the assessment results into different levels of quality: *minimum*, which ranges from 0.51 to 1.50; *recommended*, which ranges from 1.51 to 2.50; and *optimum*, which ranges from 2.51 to 3.00. If the evaluation result is 0.50 or less, QUARQ classifies it as unsatisfactory, meaning that the evaluated object didn't reach the minimum standards. At the neighborhood scale, QUARQ considers five evaluation criteria: *articulation* (how the private areas relate with open areas and how accessible the open areas are), *personalization* (how residents can change or intervene in the built space), *pleasantness* (related with environmental comfort), safety (how safe the place is regarding daily activities and protection against robbery), and *spatial adequacy* (proper

offering and dimensioning of open spaces).

Verniz (2020) shows in detail how the assessment of Santa Marta was performed, but a brief summary of the results is provided below. Table I summarizes Santa Marta evaluation results, showing that it scored at least the minimum in all criteria. In personalization and safety, it scored above the minimum. In our research, we developed strategies to raise the scores in articulation, pleasantness, and spatial adequacy above the minimum standards too.

| Parameters | Result | Quality Level |
|---|---|---|
| Articulation | 1.25 | Minimum + |
| Personalization | 2.87 | Optimum - |
| Pleasantness | 1.20 | Minimum + |
| Safety | 1.51 | Recommended - |
| Spatial Adequacy | 0.94 | Minimum - |

Table 1
Results of the evaluation of Santa Marta

Regarding articulation, the assessment results showed that the settlement lacked a proper and safe circulation network. The physical characteristics addressed regarding this criterion were related to the improvement of the general conditions of the circulation network, namely, pathways, ramps, and stairways. The recommendations were:

1. To protect with handrail pathways that present potential risks for pedestrians;
2. To establish a minimum circulation width that complies with accessibility standards;
3. To establish proper dimensioning parameters for stairways;
4. To establish a maximum inclination for ramps in open areas.

The assessment results in pleasantness showed that the settlement had poor waste management and collection. Also, the orientation of buildings privileged topographic features over insolation. Although the high slope of the terrain needed to have an important impact on building orientation, solar orientation should also be taken into account. The physical characteristics addressed in this criterion were related to the inclusion of shaded opened areas and waste management. The recommendations were:

5. To provide more shading in open areas;
6. To provide bins in open areas and to improve the waste collection system.

The assessment results in spatial adequacy showed that the settlement lacked urban furniture. Additionally, although it had leisure areas for different age groups these areas lacked proper furniture. The physical characteristics that were addressed in this criterion were, thus, related to a better detailing of buildings, leisure areas, and commerce. The recommendations were:

7. To establish a minimum building area to accommodate at least one dwelling unit per floor;
8. To provide adequate leisure areas, properly equipped with urban furniture that is suitable for children, teenager, and adults/seniors;
9. To provide adequate areas for commerce;
10. To provide proper urban furniture: benches, light poles, and bins in open areas.

These ten recommendations guided the transformation of the analytic grammar, the Santa Marta Urban Grammar, into a synthetic grammar, the "Planned Favela" Urban Grammar.

## PROPOSING A SYNTHETIC SHAPE GRAMMAR

The analytic grammar encompasses a set of fourteen rules that account for the generation of buildings and circulation, encoding the settlement process of the Santa Marta favela. To attend the recommendations of Santa Marta favela's assessment results, we changed and added rules to the analytic grammar. Figure 1 shows some of the transformation performed on the rule level to turn the Santa Marta Urban Grammar into the Planned Favela Urban Grammar. Arrows with straight lines represent rules that were kept unchanged, arrows with curvy lines represent rules that were changed, and arrows following a plus sign represent rules that were added to the grammar.

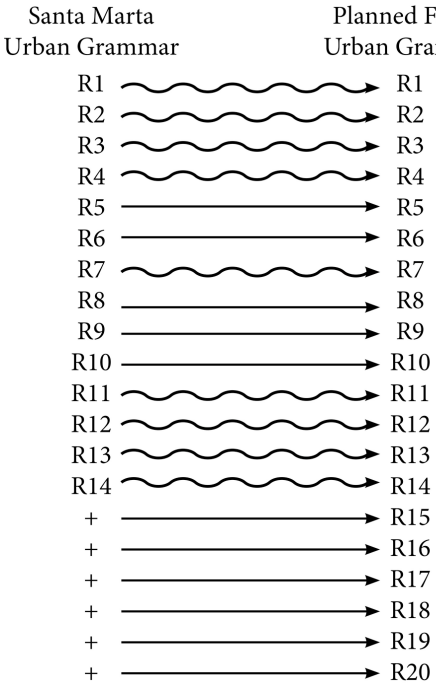


Figure 1
Meta-transformation of the analytic grammar's rules into the synthetic grammar's rules.

### *Changed rules*

Recommendations 1, 2, 3, 4, and 7 were related to the improvement of physical features that were already included in the analytic grammar. These features are circulation detailing (adding handrails and establishing a minimum width, 1 and 2), stair tread depth (3), stair rise height (3), ramps inclination (4), and the building footprint (7). Changes were performed in all the existing rules that had variables related to those physical characteristics. These rules are R1, R2, R3, R4, R7, R11, R12, R13, and R14 and changes were made in two ways: by changing parameters already included in the rule or by adding new parameters to the rule. Figure 2 shows an example of changes made to an existing parameter. It shows, in red, the changes in rule R3. The parameter "dB-S1" refers to the circulation width. In the analytic grammar 0.25 m < d B-S1 < 8.50 m and in the synthetic grammar 0.90 m < dB-S1 < 8.50 m. With this change, the minimum width of the circulation became 1.80 m.

Figure 3 shows an example of changes made by adding a parameter. It shows, in red, the changes in rule R11a. The parameter "h" is added to the synthetic grammar to represent the inclusion of a handrail in pathways where the inclination is more than three degrees.

### *Added rules*

Recommendations 5, 6, 7, 8, 9, and 10 are related to the inclusion of physical features that the analytic grammar does not account for. These features are the existence of shading in open areas (5), bins in open areas (6), trash containers in open areas (6), urban furnishing (8 and 10), and commerce buildings (9). Rules R15, R16, R17, R18, R19, and R20 were added to include the detailing of these features.

Figure 4 shows an example of an added rule. Rule R15 adds a label to distinguish between buildings that will be used for housing (R), commerce (C), or turned into an open area (O).

## VALIDATION

To validate the synthetic grammar obtained after the grammatical transformations described above, we developed a derivation of a small settlement next to Santa Marta favela, which we called "planned favela", using the synthetic grammar. Then we evaluated the "planned favela" using QUARQ. Figure 5 shows the first nine detailed steps of the derivation, Figure 6 shows the simplified derivation of the planned favela, and Figure 7 shows the resulting planned favela with urban furnishing.

The transformation of the analytic grammar focused on improving articulation, pleasantness, and spatial adequacy. Table 2 shows the comparison of the results of the assessment of the Santa Marta favela and of the "planned favela" in these criteria.

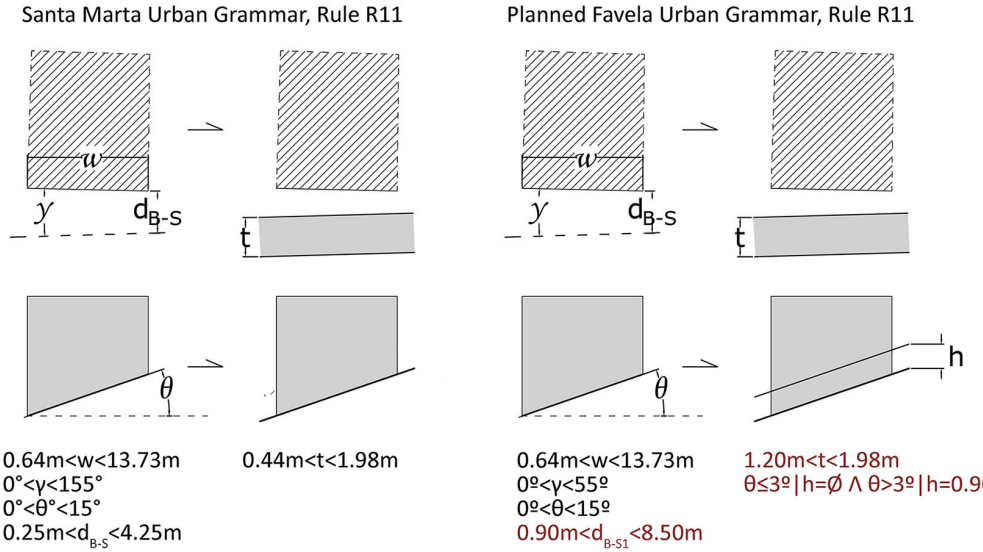


Figure 2
Comparison between Rule R3 of the analytic grammar and R3 of the synthetic grammar

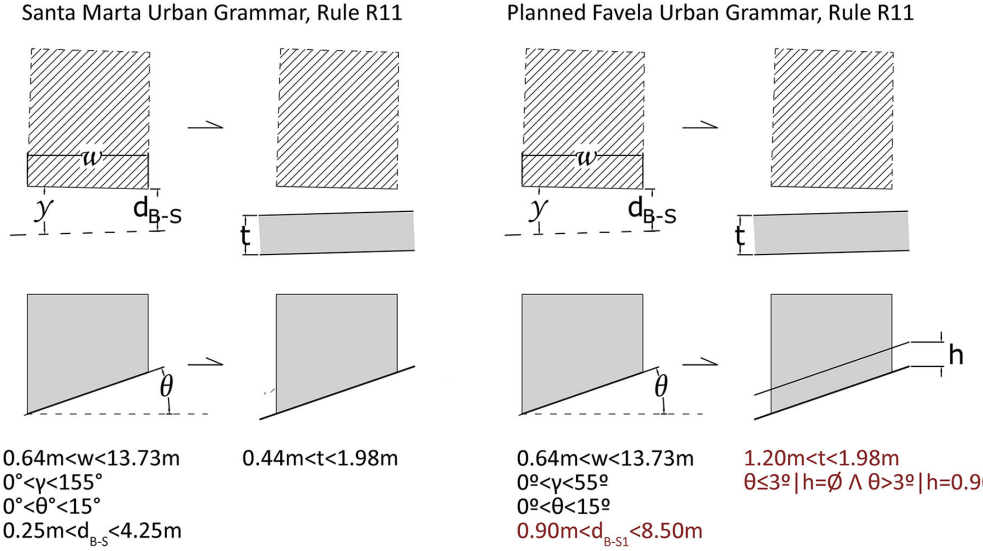


Figure 3
Comparison between Rule R11 of the analytic grammar and R11 of the synthetic grammar

Figure 4
Rule R15 of the synthetic grammar

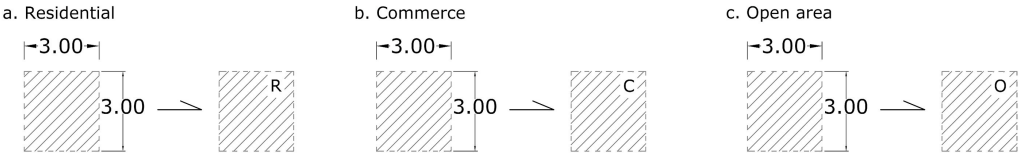


Figure 5
First nine steps of the derivation of the new favela

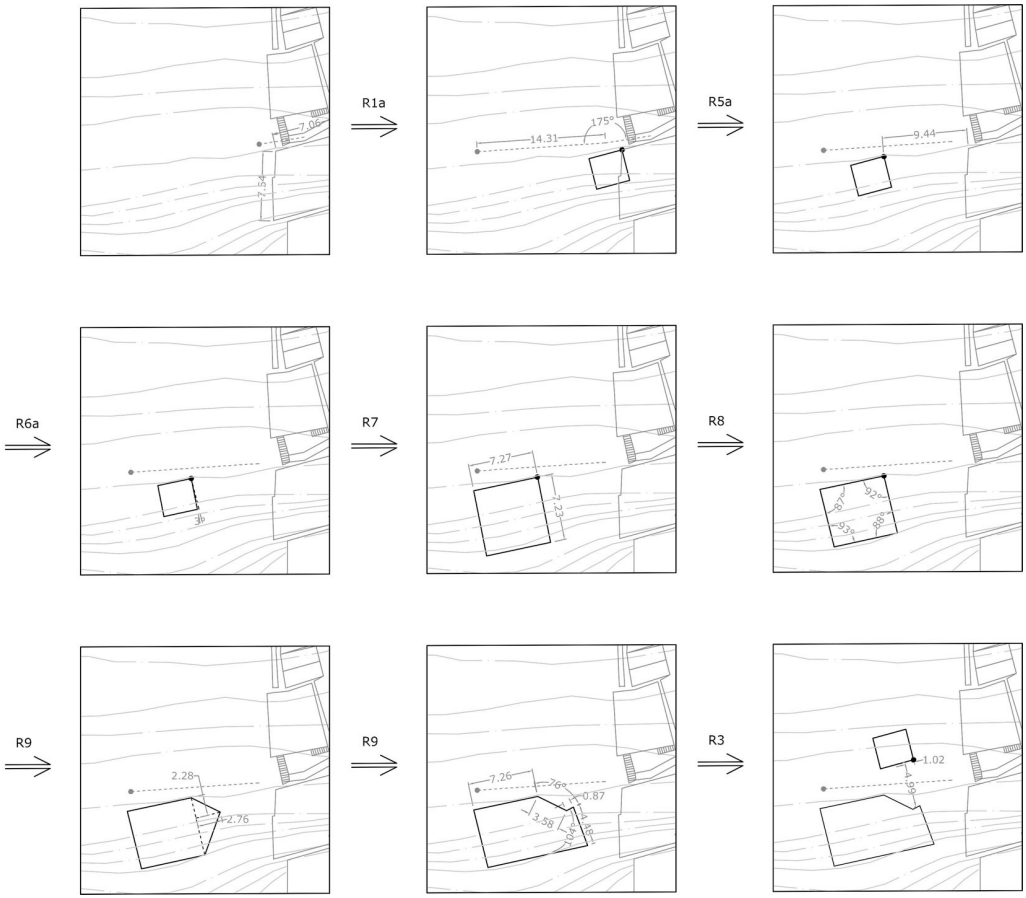


Table 2
Comparison of the results of the Santa Marta favela assessment and the planned favela assessment

| Targeted criteria | Santa Marta favela | Planned favela |
|---|---|---|
| **Articulation** | **1.25** | **2.13** |
| **Personalization** | 2.87 | 3.00 |
| **Pleasantness** | **1.20** | **2.11** |
| **Spatial adequacy** | **0.94** | **1.93** |
| **Safety** | 1.51 | 3.00 |

The comparison of the assessment results showed that scores in all criteria increased from the Santa

Figure 6
Simplified derivation of the planned favela using the synthetic grammar rules

Marta favela to the planned favela. Scores in articulation increased by 70%, pleasantness by 76%, and spatial adequacy by 105%. Additionally, non-targeted criteria scores also increased, by 4% in personalization and by 99% in safety. In both personalization and safety, scores reached the highest quality level.

## SUMMARY AND CONCLUSIONS

In this paper we presented a strategy to create a synthetic grammar from an analytic grammar, which was developed and applied to change an analytic grammar encoding the settlement process of a favela in Rio de Janeiro, Brazil, into a synthetic grammar to design new, favela-like settlements. The favela is Santa Marta and it was shown to be representative of favelas in steep terrains. The goal is to use the synthetic grammar to design settlements in similar terrains that share the qualities but not the flaws of favelas.

The key element in the strategy is to use Knight's grammatical transformations to change the analytic grammar into the synthetic grammar. To perform this transformation, we applied an established housing evaluation system called QUARQ at the neighborhood scale to assess Santa Marta. The assessment results permitted to identify those criteria in which the favela ranked lower, which were pleasantness, spatial adequacy, and articulation, and yielded recommendations on how to improve them. The grammatical transformation then targeted rules defining the physical features that had an impact on these criteria. The transformations included changing existing rules and adding new rules. To validate the work, we used the synthetic shape grammar to generate a planned favela that was evaluated using QUARQ. By comparing the evaluation of the planned favela with the evaluation of Santa Marta we could verify that scores improved in all the criteria, not just on the targeted ones. This improvement validates the strategy used to obtain the synthetic grammar, as well as its use in the design of new settlements that meet existing standards.

The main contribution of the research is a grammar-based framework for designing new urban areas in steep terrains inspired in favelas. Although applied to a specific case, this framework can be applied to other design problems, following a similar strategy, which includes the following steps: modeling appropriate precedents used a case (modeling), inferring an analytic shape grammar encoding the case (encoding), evaluating the case using a valid assessment tool (evaluating), transforming the analytic shape grammar into synthetic shape grammar (changing), and validating the results of the synthetic

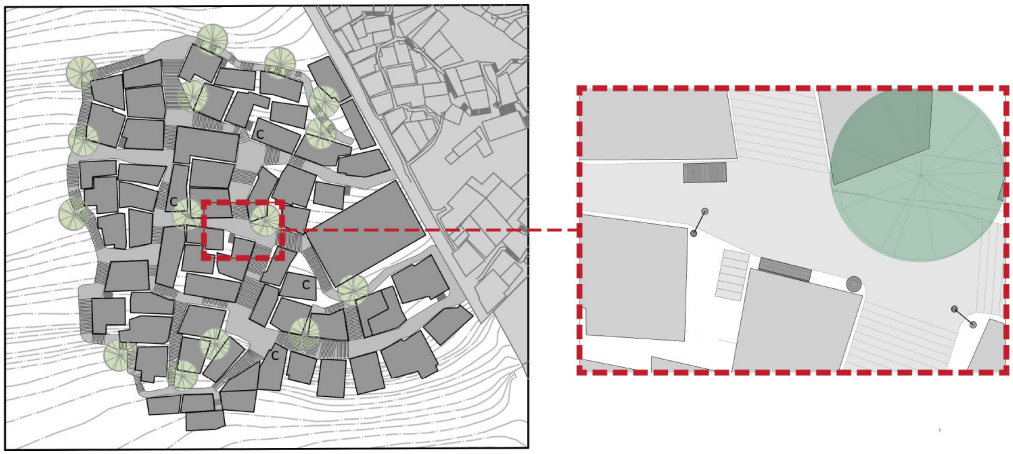

Figure 7
"Planned favela" generated using the synthetic grammar. The detail shows the urban furnishing

grammar using the same assessment tool (validating).

Informal settlements can also benefit of this synthetic grammar. The rules can be translated into a construction guide for the residents to follow. This guide can be distributed by local resident's associations, which can also be responsible for raise awareness on the importance of the guide to construct a better environment in the neighborhood.

The synthetic grammar can also be improved by adding other variants in the assessment phase, improving other characteristics of informal settlements that were not addressed at this stage of the research.

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# Designing Intradiegetic and Extradiegetic Spaces for Virtual Reality

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*Fictions for virtual reality are mostly conceived either in an entirely virtual environment or in a real environment with very little transformation. It is infinitely rare to find examples of sets designed and built specifically for a 360° experience. Building, rather than remaining purely virtual, raises complex questions about the organization of a ``space to play'' and therefore how to produce a narrative for immersion and create a 360° film grammar.We thus have created a first 360° set for the famous director Marc Caro, for whom the question of off-screen raised a very complex technical problem regarding lighting, visual effects, staging, blocking and acting. In this contribution we will show how this was solved and why the definition of a 360° narrative grammar is crucial. These are important intricacies that place the user-spectator in the optimal conditions to appreciate the experience.*

**Keywords:** *360° cinema, Virtual Reality, Methodology and pedagogy, narrative grammar, Set construction, Isovist 3D*

## INTRODUCTION

Announced several years ago, the generalization of Virtual Reality and 360° films in our image consumption habits is only being realized very gradually. The constraint of owning specific equipment coupled with a still uncomfortable practice hinders the massive adoption of 360° content in the leisure field. However, the year 2020 may be the year of the long-awaited breakthrough if the consequences of the pandemic allow it. The availability of user-friendly equipment such as the Oculus Quest or the HTC Cosmos and the multiplication of camera models, some at very attractive prices, could boost the market. Nonetheless, the production of content is abundant and the many festivals around the world are distinguishing works of exceptional quality that radically renew our relationship with filmed narrative. The creation of 360° content infuses the field of research, but little in schools, be it cinema, art or architecture. Like a little more than a century ago, when cinema established itself in the landscape of artistic production, know-how precedes theoretical knowledge, action produces reflection, example guides theoretical construction, the multiplication of propositions allows us to discern constants.

For us, who introduced 360° narration at the Ecole Nationale Supérieure d'Architecture in Nantes 20 years ago through interactive 3D universes designed in WRML, the technical stakes of immersive tools have been confronted with almost ethical issues of redefining prerogatives for architects. The resistance of the professional world, reflected in the

Figure 1
360 view from the set. Sets for 360° films are extremely rare. The construction of a real set helps to understand issues and solutions for a virtual reality experience. Photo M. Kolchesky

pedagogy of schools and more generally in schools of architecture, has paradoxically given our studio an *avant-garde* and innovative aura that pushes us to an even deeper exploration of a 360° narrative grammar.

We made the bet very early on that animated and then interactive digital images would become essential tools for architects. We anticipated software developments and monitored what was going on in the world of video games in order to catch a glimpse of the graphical improvements of the rendering engines. Cinema is also a constant reference. Although our students are big consumers of film images, whether from a movie or a series, few of them know the fundamentals of writing for the screen and how one can, without talking, depict a situation, portray a character, anchor a story in a space and time. The construction of a pedagogy based on narrative design has, over the years, made possible the development of two fields of research, the first one concerning the writing of content intended for immersion and the other one the design of devices hosting immersive experiments (LESCOP&AI. 2018).

In the set that we have created, the "grand salon" is thus raised, it gives this part of the set the feeling that it is a place of power and decisions, it is a landmark when it comes to knowing when history will take an important turn. The spaces of the pods, on the sides, like rotating barrels that are embedded in the main set, are like insert shots, they draw attention as if actors were developing a parallel action. We also have a control console located close to the camera which provides the equivalent of close-ups on the actors and insert shots and details of hands and buttons as they are viewed.

## CURRENT UNDERSTANDING: ISSUES

360-degree sets are quite rare (Figure 1). The exploration of filmed productions shows either purely digital productions or films shot in real environments. Browsing through the catalogues on offer easily proves this. In the design of this first set, which we launched in 2018, the aim was to design and build in the same way as we would do in the film industry, but with the constraints of 360° filming in mind. This particularly concerns the issue of the technical off-screen, which must be designed to hide elements that do not have to be seen in the image. The creation of a 360° set for a filming for virtual reality headsets implies a large number of precautions to be taken if we do not want to be harassed by a large

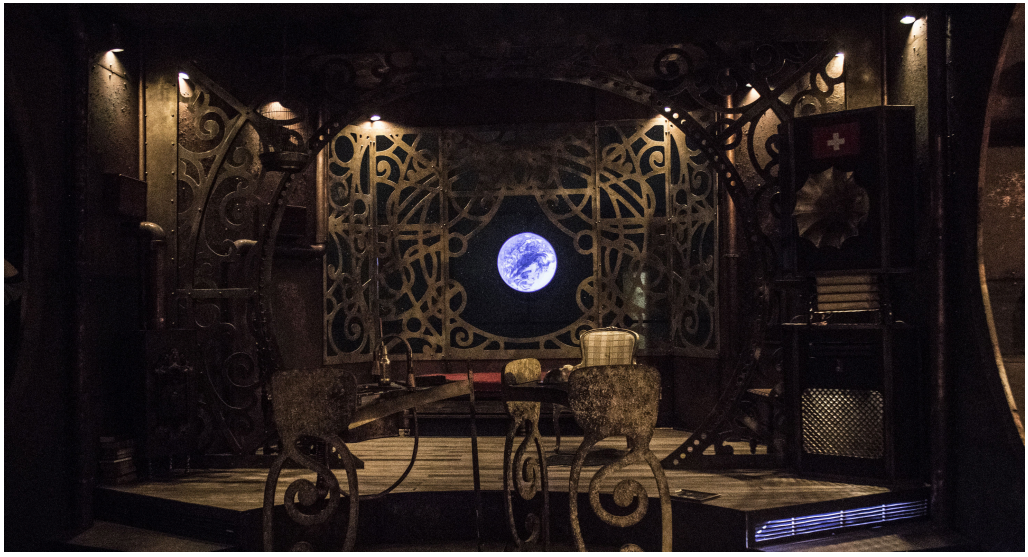


Figure 2
A real set for a 360° virtual reality film. Photo P. Lescure

amount of post-production work. First of all, the acting space should not be too large. We have noted that beyond 3 meters from the camera, the details are not really discernible anymore, both because of the resolution of the cameras and, for the moment, the main obstacle, the resolution of the screens in the headset. This gives, for a fixed camera, a diameter of 5 to 6 meters in which it is possible to install a set of actors. However, it is possible to create background spaces or very large backgrounds, which gives a real feeling of openness, but one cannot place narrative elements that would not be well discriminated by the spectator. It should also not be to the detriment of the need and willingness to understand and empathize with the actors' acting (Figure 2).

Unlike what one would generally imagine, 360 degree film for a virtual experience is not an extension of the classic film. With a 360° camera, it is indeed not possible to frame in close-up or medium or overall. It is up to the filmed character to adjust these shot values by getting up more or less close to the camera. With care, however, the short focal lengths of the cameras soon produce grotesque effects. Similarly, high angle or tilt shot will not easily be possible. If it is feasible to move the camera (slowly) to reframe the scene, it will be preferable, as in the theater, to build in parts of the set that allow a view from above or the opposite angle. The staging will position the characters in the right place at the right time to achieve the desired visual effect (Figure 3).

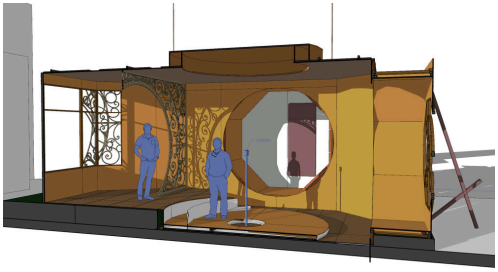


Figure 3
Section of the set: the camera is in a central position. To create a tilt shot, the ground is raised while the camera itself can be lowered a bit. Model Archirep Studio, rendering L.Lescop

Panoramic framing also implies that the lighting system should be integrated as much as possible into the diegetic space. This requires imagining solu-

tions to dim the light and to avoid hot spots that are unattractive by burning part of the image.The other challenge is to properly distribute the lights sources. A scene where the light would be concentrated in one point would complicate the stitching, that is to say the assembly of the various filmed views to compose a 360° image. This is one of the problems encountered when filming outdoors in natural light and when the sun is very bright. It is also what distinguishes the qualities of cameras on the market.

## RESEARCH QUESTION: WHAT KIND OF NARRATIVE GRAMMAR FOR A 360° VIRTUAL EXPERIENCE

The testing of the construction materializes theoretical questions about narrative grammar for virtual reality (Figure 4). The first set of questions concerns the transposition of the composition of a frame from a plane image to a 360° image. We have seen that it is obviously not possible to change the framing of a shot with a panoramic camera, but it is possible to organize the space and the movements in this space to suggest close-ups, inserts, wide area shots and even camera movements such as panning or traveling. There is another element of film grammar that concerns editing. Kulechov and his pupil Eisenstein showed very early in the history of cinema how to give meaning and symbolism through editing.In immersion, as we mentioned, direct transposition is not possible. A succession of sequences can be considered, but transposing the art of editing is against the very nature of the medium. In fact, the search for an equivalence with cinema wears itself out rather quickly. On the other hand, analogies with the theater are much more fertile. In the same way as in the theater, the playing space is entirely delivered to the spectator and as in the theater, pace, which could be compared to the editing process, the dynamics are given by the actors' performance (Pavis 2013). Intense, stirring, voluble, it induces haste and forward running, calm and soothed, it will transmit feelings of dullness or serenity. And as in the theater, overframing can be done by set elements or by light.

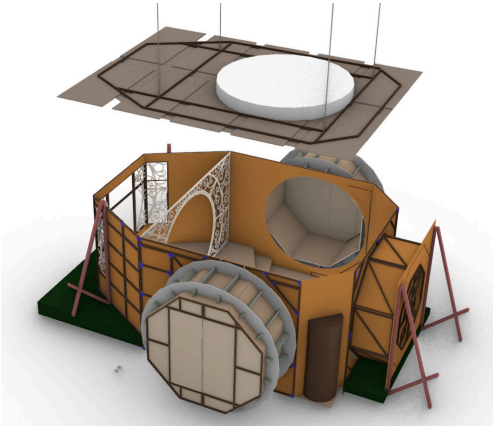


Figure 4
3D model of the set.

Figure 5
Film director Marc Caro staging at distance. Photo P.Lescure

Narrative implies the appropriation of a point of view. This point of view facilitates empathy with the characters and gives the story its tone. In 360° virtual reality, the point of view requires an intra-diegetic viewpoint. The spectator is physically in the story and for this reason asks for his position to be clarified. There are three kinds of points of view. In the first, the spectator is a ghost and his presence, invisible, does not disturb the course of the story. In the second, the spectator is present in the story as an inactive witness and in the third, he is a participating spectator-actor, which, consequently, requires a decision on whether or not to show a visible body. Many examples illustrate all these solutions, resulting in works ranging from passive contemplation to active participation.

The actors' acting is also to be compared to that of the theater. The movements must be fairly clearly expressed and the gestural dynamics must be legible. During the shooting of the film *Dans la Lune* with Marc Caro, we saw a clear difference in the cultural background between the actors from the theater and those from television and cinema. Staging of the actors did not follow the same standards as in cinema, but rather those of the theater staging. Filming at 360° requires that the director cannot be physically present on the set, he has to be at a distance, which confuses film actors (Figure 5). Before clapping, all the indications must be incorporated and the adjustments are marginally made during the play.

The question is therefore to understand how the extra-diegetic space will shape an efficient intra-diegetic experience, according to two criteria: a space to play and create when the design process is carried out and a space of astonishment and fascination when the experiment is made. We believe that these questions lead to the definition of a narrative grammar for a 360° virtual experience.

## FINDINGS: DESIGNING THE OFF-SCREEN

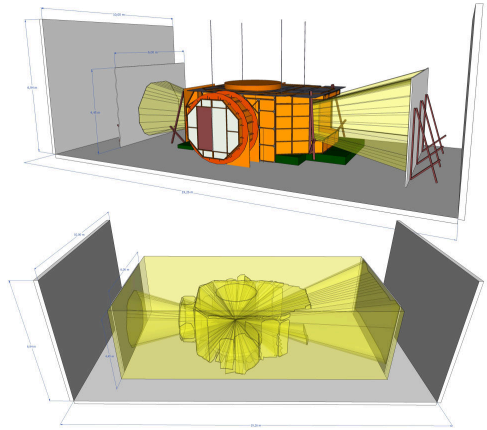
Figure 6
Off-screen visible outside the set. It is where extra-diegetic light are installed. Photo P. Lescure

It is quite obvious to think that in a 360° space the off-screen no longer exists. In fact, it's more complicated than that, and the off-screen still exists, it's just defined differently. Traditionally, the off-screen is that space that is not seen outside of the stage frame in a theater or the camera frame in a movie. The off-screen therefore has two main functions: it extends the diegetic space into the spectator's imagination (the spectator imagines continuities in what is hidden from him), and the off-screen offers opportunities for the technicians to install equipment that helps in creating the image: usually, we will find off-screen projectors, microphones, and many other things (Figure 6). So there are two kinds of off-screen depending on whether you are a spectator or a director, for the first it is the projection of the imaginary, for the second, the technique.

This frame that defines the off-screen is moving in RV, it means that nothing can escape the view, which can greatly hinder the shooting process. Céline Tricart has well described the constraints of shooting at 360°. For her film *Marriage Equality VR* shot in 2015, the great difficulty was to hide the technical team, who in the bushes, who in the trees, who behind street furniture (Tricart 2017). The off-screen should therefore no longer be defined as being outside the filming frame, but rather outside the field of vision. It is no longer to be considered laterally, but in depth. This means that the off-screen becomes what is out of the field of vision. For the construction of our set, it was consequently necessary to determine this out-of-field of vision, which was done with the help of the Isovist. From a given point, it is possible to fire rays in all directions and thus visualize the portions of space seen and the portions of space hidden. In this way, we were able to determine, by making the point of the ray shooting coincide with the camera's point, the volumes of space invisible to the eye, our famous deep off-field. These volumes can therefore be occupied by technique or by accessories, we are certain that they will not be visible to the camera.

The decor being a confined space, the problem was relatively simple, it mainly concerned the placement of the background visible through the bays of the spacecraft. As the background was painted on a constructed support, the distance and surface had to be very precisely adjusted to match the physical constraints of the studio. To do so, we used the T4SU tools developed by Hartwell and Leduc (Hartwell-

Leduc 2016) dedicated to sunlight, but with a very good Isovist module (Figures 7, 8). T4SU is a free plugin, developed for Sketchup. It calculates cones of visibility from a given point and thus gives the volumes of vision. It is also possible to have the area of intersection between the volume of vision and the affected surfaces, which allowed us to determine very precisely the areas to be worked on for the set. Grasshopper definitions were also tested, but T4SU's ease of use made it the preferred tool (Figure 9). However, for future developments, we know that a Grasshopper definition will allow us to obtain the unseen volumes, which will be very useful for more complex sets.



The isovists used to determine the off-field of the 360° camera set have also been tested to understand the resolution issues of the 360° camera. Indeed, quite logically, a single pixel will cover a larger area as the distance increases. We can therefore establish a relationship between the distance of the surfaces of the set and the resolution of the details to be built or painted. It is useless to put a poster at a distance if it will be barely visible or readable. And, once again, the additional constraint doubles with the definition of the media to see the film, quality headphones or telephone. To meet the standard of the market's systems today, we have opted for a definition of 3840x1920. It is an equirectangular image that will then be mapped onto a virtual sphere. So there are 7,372,800 pixels to be distributed, with each pixel describing a projected surface area that can be determined. We do not really need a very complex calculation to guide us in the creation of the scenery, on the other hand, knowing that at a certain distance the resolution will already be half as high makes it possible to greatly anticipate the way in which visual information will be processed. It is the orders of magnitude that are interesting.

A fairly simple definition has been put together. The set modeled in Sketchup is imported with the Trimmed Planes option in order to have some Breps. In Sketchup, each object has been grouped and put on a different layer for an easier management afterwards. In Grasshopper, a point is placed which indicates the position of the camera. A UV sphere is used to visualize the resolution of the image. A vector follows the normal of each face of the sphere. A collision test is performed between this vector and the set and the background. This creates a volume which is then tested in Boolean operation with the elements of the set. It is the footprint of the tiling of the sphere that gives a grid printed on the decor and thus gives an idea of the resolution of the image as a function of distance (Figures 10, 11).

At the moment, Grasshopper's tests show errors if the resolution of the sphere is too high. This question will be the subject of further tests.

Figure 7
One of the key issue is to only construct what is going to be seen in the image whatever the format is. Isovist helped defining the available surface for the background, and then the built result. Illustrations L.Lescop

Figure 8
Positioning of the background for projection or post-production. Photos L.Lescop

Figure 9
Except of the Grasshopper definition. Ill. Lescop

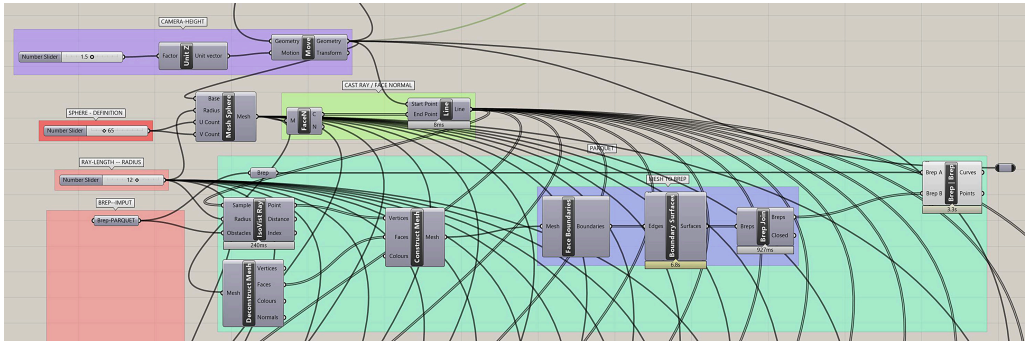


Figure 10
Definition grid calculated with Grasshopper. Ill. L.Lescop

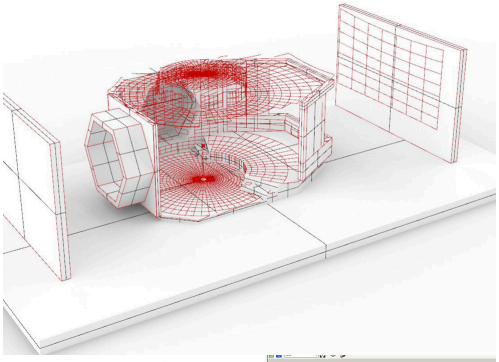
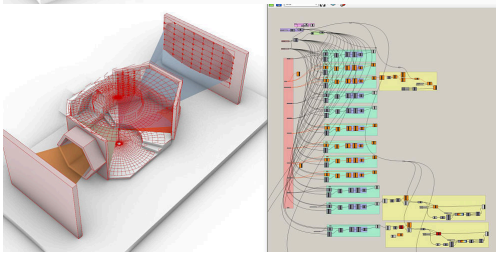


Figure 11
Visualization of the 360° image resolution with a grid. Ill. Lescop



## CONTRIBUTION: WRITING FOR A 360° REAL-VIRTUAL SPACE

One of the first conceptual obstacles concerning 360° writing or more globally for immersion is the relation to temporality and more specifically to what is called "real time".Immersion, lived as an embodied experience, may imply that temporal continuity is made identically or at least according to the same rules. However, the very nature of the concept of narrative implies the mastering of the temporality with which it will be played out. The creation of a narrative rests on the choices made in the organization of time, which can be accelerated, slowed down, cut or shifted at will. It is this very reorganization of temporality that makes a narrative; without it we are only in a voyeuristic posture waiting for an uncertain event. In the world of cinema, Robert McKee's book "Story" serves as a reference to describe the stakes of the filmic narrative (McKee 1997).

Writing for 360° therefore requires controlling a space and a time that are not necessarily the equivalent of reality, but rather perceived rhythms that match the beats of the narrative. To put it another way, the narrative does not take place in a continuous space-time but in a discrete space-time. An illustration of this transformation of a contained space into a discrete space can be found in the world of video games. The game GTA (Grand Theft Auto) faithfully reproduces the city of Los Angeles in its opus V, which can be travelled in all directions at will. The game is part of a narrative logic, however, and for this reason the stakes must be renewed to maintain interest. Two different temporalities coexist, that of the diegetic space and that of the player. While one has

Figure 12
Dans la Lune, during the shooting. Above on set, bellow outside the set in the control area. Photo M. Kolchesky, montage L. Lescop

the feeling of living everything "in real time", a whole day lasts only 8 minutes while a full hour passes in 2 minutes without having the feeling of being in an accelerated time.The space that is supposed to be embedded in reality also has ellipses and finds shortcuts to go from one point of interest to another. This narrative ellipse, which in a cinema montage would have been a cut, is in GTA the juxtaposition of two distant spaces, which made us say that there has been a conversion from time to space. (Lescop 2019)

The complexity clearly comes from the medium itself. Immersed in an experience of virtual reality, the time it takes to install oneself in the diegetic narrative is relatively long, one has to find one's markers and find one's bearings, whereas events can arise from any place (Figures 12, 13).This therefore implies the use of sequences of relatively long duration, or even the use of a single shot and a play for the actors close to that of the theater or the first films at the cinema. One of the most important issues that authors and directors writing on the subject try to understand is how to focus the spectator's interest on a particular point of virtual space (Nielsen&al.2016), (Elmezeny&al. 2018), (Pillai&Verma 2019). Jessica Brillhart (Brillhart 2016) was one of the first to theorize about the creation of points of interest that will, like spatio-narrative beacons, refocus the viewer's attention where the director wants the action to be observed, what she called: probabilistic editing theory. This focusing, motivated by a sound signal or by a form of visual appeal, only partially resolves the management of the narrative space.

Figure 13
Preparing the shot. Photo P.Lescure

Figure 14
Building the set.
Photo L.Lescop

There are three different attitudes to the development of a narrative: the spectator can be synchronous with the unfolding of the events, he discovers the events at the same time as the protagonists, and the narrative follows the rhythm of these discoveries. Second option, the spectator is late relative to the protagonist(s) in the unfolding of the events. The narrative progresses by the succession of revelations that make the spectator catch up on the data of the events. Third option, the spectator is in advance and has better information than the protagonist(s).This is a bit like the "Punch and Judy" effect where we know that the gendarme is hidden behind the curtain. Abundantly used by director Alfred Hitchcock, this process works on the spectator's anticipation of the course of events and on the screenwriter's ability to work on time or to produce false leads (Snyder 2005)

## FURTHER DEVELOPMENTS

Offering a space in which a maximum number of constraints can be anticipated, a constructed set invites us to develop formal answers to theoretical questions (Figure 14). This exercise, combining research and pedagogy, in which we are involved while observing an emergent process that will radically disrupt our approaches. As mentioned at the beginning of this article, two headsets making a radical breakthrough appeared during the second half of 2019: the Oculus Quest and the Vive Cosmos. These headsets, especially the Quest, have been characterized by their ability to offer a free experience, without any physical connection, over an extremely wide area of action. This means that we enter a new universe in which the spectator is really a spectator-actor interacting with what is happening around him. Entirely new paradigms are thus being put in place, paradigms that shall be on the agenda of our forthcoming teachings.

## ACKNOWLEDGEMENTS

*We would like to thank the director Marc Caro for the inspiration he has given us, the teaching colleagues who have been with us for many years now and above all the students of the "Archirep" option who have inspired us all these years with their talent and involvement.*

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# Decision-Making as a Social Choice Game

## *Gamifying an urban redevelopment process in search for consensus*

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*The paper reports the formulation, the design, and the results of a serious game developed for structuring negotiations concerning the redevelopment of a university campus with various stakeholders. The main aim of this research was to formulate the redevelopment planning problem as an abstract and discrete decision-making problem involving multiple actions, multiple actors with preconceived gains and losses with respect to the comprising actions, and decisions as combinations of actions. Using fictitious and yet realistic scenarios and stakeholders as simulation, the results evidence how different levels of democratic participation and different modes of moderation can affect reaching a consensus and present in a mathematical characterisation of a consensus as a state of equilibrium. The small set of actions and actors enabled a chance to compute a theoretically optimal state of consensus, where the efficiency and the effectiveness of different modes of moderation and participatory rights could be observed and analysed.*

**Keywords:** *Serious Game, Consensus Building, Democratization, Game Theory, Social Decision*

## INTRODUCTION

In this research, a playable serious game was designed to simulate the further development of a university campus in the following decades, taking into account the cultural significance of the old campus buildings, even if not all buildings are listed as cultural heritage, nor is the campus a conservation area. The existence of cultural heritage challenges the ideas of planning that are strongly influenced by ordinary cost-benefit analyses. This paper shows how the discretisation of a multi-actor decision making problem can help structure a spatial planning problem as a participatory/gamified planning process, and pave the way for analysing such strategic planning decisions using the conceptual frameworks of graph theory and game theory.

The UNESCO 2011 Recommendation on the Historic Urban Landscape promotes greater inclusion and democratization of heritage planning, and wherever needed, make use of participatory tools to find

consensus by the key stakeholders (Pereira Roders, 2019). However, stakeholders often perceive heritage differently, and they typically have different kinds of stakes or concerns with respect to the redevelopment of an urban area (e.g. an urban university campus), thus conflicts can naturally arise between them in a planning process. As such, negotiation and finding consensus can be like a puzzle to find an optimal solution for (Bots & Hermans, 2003; Mayer et al., 2005). While such puzzles are not necessarily insolvable, the stakeholders participating in the puzzle may need external help to realize the existence of win-win solutions to avoid falling into any dilemma(Cunningham & Hermans, 2018). The conflicting opinions on various actions and their consequences could be understood by stakeholders by getting them involved in 'simulation games', i.e. games simulating the decision-making processes, especially construction and management [strategy] games as defined in (Rollings & Adams, 2003). Such games offer chances to experience other points of views and thus potentially help reach consensus more effectively (Werner, 2017).

## GAME DESIGN AND SETTINGS

The main objective of this research is to frame a campus redevelopment planning process for TU Delft as a multi-actor/multi-criteria decision-making process, to be simulated as a social decision/strategy game (Jackson, 2014). As this game seems to have the potential to be generalized to other urban redevelopment planning cases, we formulate the problem mathematically and computationally, in order to provide for further analysis with graph theory and game theory (Easley & Kleinberg, 2010), as well as computational simulations with a larger number of iterations using agent-based models.

In the game design, agents (stakeholders) $A$, objects (sites) **o**, choices available for those objects **c**, and decisions **d** consisted of choices per each object in our game. The notation of these items and their relations are mentioned in Table 1 and Table 2. All the agents are directly or indirectly related to the campus redevelopment issue, thus having their own preference and judging criteria. The decisions will change over different rounds during the game, meaning some of the decisions from the set $D$ will be eventually discovered over time, which we denote with a time superscript $\mathbf{d}^{(t)}$ as customary in the study of Markov Chains. For example, the starting situation $\mathbf{d}^{(0)}$ is also considered to be a decision (which entails doing nothing, but also keeping all states the same as they are).

A preference type function $\Theta$ is defined for agents, describing their preference, objection, or indifference regarding the choices applicable to objects. The preference type of each specific agent on possible scenarios of campus development is deduced from their online-accessible profiling and reports. For any decision $\mathbf{d} \in D$, we can define a utility mapping function $\mathrm{u}(a_i, \mathbf{d})$ for each agent $a_i$ that checks the corresponding value in $\theta_i$ for all the choices indexed with respect to objects in **d**, and returns the sum of the preference type values. This utility value is used to determine the corresponding vote decision $\varphi_i$ of an agent $a_i$ based on the voting function $\varphi(a_i, \mathbf{d})$ (cf. Table 3).

By adjusting the values of $\lambda_{i-}$ and $\lambda_{i+}$, different voting strategies of agents can be described, which may allow for compromising, bargaining, trading-off and/or paying-back as an entity. However, for the sake of simplicity, a high value was assigned for the ratio of the two parameters for all the agents, where

| Description | Notation | Notes (Example in our game) | |
|---|---|---|---|
| A set of all agents (stakeholders) | $A = \{a_1, a_2, \dots, a_n\}$,<br>$A = \{a_i \mid i \in [1, n]\}$ | ($a_1$) the general municipality of the city<br>($a_3$) the executive board of the university<br>($a_5$) a student representative of the university<br>($a_7$) the industrial park in the south of the campus<br>($a_9$) a citizen/alumina working in the industrial area | ($a_2$) the heritage manager of the city,<br>($a_4$) a professor from the faculty of applied sciences<br>($a_6$) the real state cooperation<br>($a_8$) a citizen representative from the city centre<br>($a_{10}$) the public transportation company of the city |
| Number of agents | $\mid A \mid = n$ | $n = 10$ | |

Table 1
The nomenclature about agents in the game

Table 2
The nomenclature of objects, choices and decisions in the game

| Description | Notation | Notes (Example in our game) |
|---|---|---|
| A vector of all objects (sites) for which an action is to be taken | $\boldsymbol{o} \coloneqq [o_j]_{m\times 1}$ | $m = 6$<br>($o_1$) University Campus North<br>($o_2$) University Central Campus<br>($o_3$) Industrial Park in Campus South<br>($o_4$) City Centre<br>($o_5$) Another Nearby City<br>($o_6$) Other Possible Sites |
| A vector of all possible choices per each object (site) | $\boldsymbol{c} \coloneqq [c_k]_{l\times 1}$ | $l = 5$<br>($c_1$) Maintain/Conserve/Preserve<br>($c_2$) Renovate/Adaptive Reuse<br>($c_3$) Densification<br>($c_4$) Selling and Moving<br>($c_5$) Constructing New Buildings on site |
| A matrix of all possibilities of object-choice pair | $\boldsymbol{S} \coloneqq [s_{j,k}]_{m\times l} = \left[\underbrace{\boldsymbol{c}\vert\boldsymbol{c}\vert\ldots\vert\boldsymbol{c}}_{m\ columns}\right]^T$ | For the first three objects, all five choices are feasible, while for the last three objects, only the first three are. |
| Number of object-choice pairs | $\vert\{s_{j,k}\vert j\in[1,m], k\in[1,l]\}\vert = m\times l$ | $\vert\{s_{j,k}\vert j\in[1,m], k\in[1,l]\}\vert = m\times l = 30$<br>An agent needs to have considered their preferences for this many choice pairs. This number is significantly less than the total number of decisions as mentioned below. |
| A decision: a vector of object-choice pairs (or a decision data-point) in a manner that there is one and only one pair per each object | $\boldsymbol{d} = [d_j]_{m\times 1} = \boldsymbol{\Pi}^{(t)}\boldsymbol{c}$<br>Where $\boldsymbol{\Pi}^{(t)}$ is a rectangular permutation matrix of size $m\times l$ at iteration time $t$ whose rows are basis vectors $\boldsymbol{e}_k \in \mathbb{R}^l$<br>$\boldsymbol{d} = \left(\boldsymbol{\Pi}^{(t)} \odot \boldsymbol{S}\right)\mathbf{1}_m$ | $\boldsymbol{d}^{(0)} = [c_4, c_1, c_3, c_1, c_1, c_1]^T$<br>is a decision (and the initial state) in our game, e.g. $c_4$ in the first position in the vector corresponds to<br>($c_4$) *selling and moving* from ($o_1$) *the TU Delft North* |
| A set of all possible decisions | $D = \left\{\boldsymbol{d}\vert\boldsymbol{d} = \left(\boldsymbol{\Pi}^{(e)} \odot \boldsymbol{S}\right)\mathbf{1}_m\right\}$<br>$e \in [0, l^m]$<br>Exhausting all possible permutations for each possible epoch will result in $\vert D\vert = l^m$ | There exists a space of possible decisions, in which not every element (decision data-point) is feasible due to the feasibility of object-choice pairs.<br>$\vert D\vert = l^m = 5^6 = 15625$<br>Among them 3375 decisions are feasible |
| An explored decision during the game | $\boldsymbol{d}^{(t)} \in D$<br>$t \in [0, \tau]$ | The iteration time of the last round is denoted as $\tau$, the game masters can observe if the same decision is being repeated. |

$\frac{\lambda_{i-}}{\lambda_{i+}} \geq m$ in this case, thus giving the objections much higher importance than the preferences. This also means that the an agent will not agree to a decision **d** even if there is only one objected choice for a particular object.

Considering the individual votes $\phi_i$ of all the agents involved, a voting configuration $\phi^{(t)}$ can be formed. Further, a transformation rule can be defined for transforming the vote to $\varphi^{(t)}$ to give "YES" votes and "NO" votes different weights, namely $1$ for YES and $-\alpha$ for NO. In this case, a relatively large value $\alpha$ was assigned to make sure that a complete consensus must be met for the decision **d**.

A vector of voting weights $\mathbf{w} = [w_1, w_2, \ldots, w_n]^T \in \mathbb{R}^n$ is also assigned for all the agents, which is an unknown parameter for the agents initially. The final voting result for decision $\mathbf{d}^{(t)}$ is thus:

$$\upsilon^{(t)} = \upsilon\left(\mathbf{d}^{(t)}\right) = \mathbf{w}^{\mathrm{T}}\phi^{(t)} \quad (1)$$

For each round of voting, $\upsilon^{(t)} > 0$ when a consensus is met, in other words, when the voting process is successful, and vice versa. The individual voting weight $w_i$ reflects multiple layers of information, which can be the social status, the decision power, the representative pool size, and the social inclusion of agents in the decision-making process. For an extreme scenario, $w_i$ can be equal to 0, which indicates that even though the agent is invited to vote, their opinion is not taken into account for reaching consensus and making final decisions, which is a cruel truth often happening in the real world.

Four different configurations of the voting weights $\mathbf{w}^{[r]}, r \in \{1, 2, 3, 4\}$ were designed, which reflect the different levels of democratisation (Bogaards, 2010). To be more specific, $\mathbf{w}^{[1]}$ and $\mathbf{w}^{[2]}$ are all in a high level of democratization, where everyone can vote, and everyone's vote counts. In $\mathbf{w}^{[1]}$ all the agents' weight equally, while in $\mathbf{w}^{[2]}$, there are hierarchies for voting weights. In practice, the agents with higher weights (importance/relevance)

| Description | Notation | Note (Example in our game) |
|---|---|---|
| Agents' Strategy indicator:<br>($\lambda_{i-}$) objection weight<br>($\lambda_{i+}$) preference weight | $\lambda_{i-}, \lambda_{i+} \in \mathbb{R}_+$ | In this game $\frac{\lambda_{i-}}{\lambda_{i+}} \gg m$, giving the objections much higher importance than the preferences |
| Preference Type Function:<br>$\lambda_{i-}$ indicating agent's objection;<br>$\lambda_{i+}$ indicating agent's preference;<br>0 indicating agent's indifference | $\Theta(a_i, \boldsymbol{S}) = \boldsymbol{\theta}_i \in \{-\lambda_{i-}, 0, \lambda_{i+}\}^{m \times l}$<br>$\Theta(a_i, d_j) \in \{-\lambda_{i-}, 0, \lambda_{i+}\}$ | The preference type $\theta_i$ of each specific agent is deduced from their online profiling and reports. |
| Utility Function:<br>mapping of preference type and decision into the utility of agent | $\mathrm{u}(a_i, \boldsymbol{d}^{(t)}) = \sum_{j=1}^{m} \Theta(a_i, d_j) \mid d_j \in \boldsymbol{d}^{(t)}$ | We use the sum of preference type of each object-choice pair in the decision as the utility mapping. |
| Voting Function:<br>Agent $a_i$ votes YES if $\varphi_i = 1$;<br>votes NO if $\varphi_i = -1$ | $\varphi_i^{(t)} \coloneqq \varphi(a_i, \boldsymbol{d}^{(t)}) = \frac{\lvert u(a_i, \boldsymbol{d}^{(t)}) \rvert}{u(a_i, \boldsymbol{d}^{(t)})}$ | This is a sign function that decides if the sign of the computed utility is positive or negative. |
| Vector of the votes of all agents | $\boldsymbol{\varphi}^{(t)} \coloneqq \left[\varphi_1^{(t)}, \varphi_2^{(t)}, \ldots, \varphi_n^{(t)}\right]^T$<br>$\boldsymbol{\varphi}^{(t)} \in \{-1, +1\}^n$ | This vector can be used as a time series or a transcript of the game, recording how each agent voted for every discussed decision. |
| Vector of transformed votes of all agents:<br>$\phi_i = 1$ if $\varphi_i = 1$;<br>$\phi_i = -\alpha$ if $\varphi_i = -1$, | $\boldsymbol{\phi}^{(t)} \coloneqq \frac{\alpha + 1}{2}\left(\boldsymbol{\varphi}^{(t)} - 1\right) + 1$<br>$\boldsymbol{\phi}^{(t)} \in \{-\alpha, 1\}^n$ | $\alpha \in \mathbb{R}_+$ indicates the relative significance of negative votes compared to positive votes, here $\alpha \geq n \frac{\max_i(w_i)}{\min_i(w_i)}$ |
| Vector of agent's vote weight | $\boldsymbol{w} = [w_1, w_2, \ldots, w_n]^{\mathrm{T}} \in \mathbb{R}^n$ | The vote weights are set for each group setting. In our game we have four different configurations, which we will denote as $\boldsymbol{w}^{[r]}, r \in \{1,2,3,4\}$ |
| Result of voting system:<br>For any explored decision $d^{(t)}$, there will be a final result. | $\upsilon^{(t)} \coloneqq \upsilon(\boldsymbol{d}^{(t)}) = \boldsymbol{w}^T \boldsymbol{\phi}^{(t)}$<br>$\upsilon^{(t)} \in \mathbb{R}$ | For each round of voting,<br>$\upsilon^{(t)} > 0$ when a consensus is met |

Table 3
The nomenclature of the preference type, utility, and vote functions

also get more chances to propose new ideas to the decision-making, this process is also mimicked in this game simulation. In contrast, $\mathbf{w}^{[3]}$ and $\mathbf{w}^{[4]}$ are all in a low level of democratization, where even though everyone is invited in the discussion and everyone can vote, not everyone's vote counts. In $\mathbf{w}^{[3]}$, only experts are given a non-zero weight, thus leading to an expert-based decision-making scenario, while in $\mathbf{w}^{[4]}$ only the ones with either power or capital including the municipality and the big companies are given a non-zero weight, thus resulting as in a capitalist scenario. All the four democratization levels are quite common in the real world.

Parallel to the voting process considering the preference type of agents, two functions $\gamma(d_j)$ and $\kappa(d_j)$ are defined that check choices per objects in the explored decision $\mathbf{d}^{(t)}$ and return the [non-monetary] gain and the [monetary] cost of making a choice for a specific object for the whole society, regardless of the individual preference or the voting result. In this game, these functions are evaluated from a look-up table with precomputed values. But in practice, they can be replaced by some environmental assessment modules. The total social benefit $\rho^{(t)}$ for the society by making the decision $\mathbf{d}^{(t)}$ can be defined as a gain-cost ratio (cf. Table 4):

$$\rho^{(t)} = \rho\left(\mathbf{d}^{(t)}\right) = \frac{\sum_{j=1}^{m} \gamma(d_j)}{\sum_{j=1}^{m} \kappa(d_j)} | d_j \in \mathbf{d}^{(t)} \quad (2)$$

A social decision game could also be regarded as an optimization problem. However, it is also argued by some scholars (Jackson, 2014) that finding a mechanism to optimize all the valued features of a social decision game can be very hard, if not impossible. For brevity, this research focuses on searching for the best-fitting decision $\mathbf{d}^{(t)}$, satisfying $\upsilon^{(t)}$ (a constraint) and maximising $\rho^{(t)}$ (an objective) of the social decision system given a game setting $(A, \mathbf{o}, \mathbf{c}, \Theta, \mathrm{u}, \varphi, \mathbf{w}, \gamma, \kappa)$.

The value of $\upsilon^{(t)}$ represents how happy each agent would be in the end about the decision $\mathbf{d}^{(t)}$. This can reflect the feature of "Individual Rationality",

Table 4
The nomenclature of the social benefits in the game

| Description | Notation | Note (Example in our game) |
|---|---|---|
| Whole society cost function for one round | $\kappa_j \coloneqq \kappa(d_j)$<br>$\kappa_j \in \mathbb{Z}$ | The costs in our game are in the range of [-20, 40] in a monetary unit. Negative costs mean benefits. For example $(o_2, c_4)$ will have a cost of 10. |
| Whole society gain function for one round | $\gamma_j \coloneqq \gamma(d_j)$<br>$\gamma_j \in \mathbb{Z}$ | The gains in our game are in the range of [-20, 30] in a non-monetary unit. Negative gains mean loss. For example $(o_2, c_4)$ will have a gain of 10. |
| Total social benefit (gain-cost ratio) for one round | $\rho^{(t)} \coloneqq \rho(\boldsymbol{d}^{(t)}) = \frac{\sum_{j=1}^{m} \gamma(d_j)}{\sum_{j=1}^{m} \kappa(d_j)} \mid d_j \in \boldsymbol{d}^{(t)}$<br>$\rho^{(t)} \in \mathbb{R}_+$ | The social benefits are in the range of [0, 1] in an abstract unit. Several decisions can reach the maximum possible social benefit 1. For example, $\rho^{(0)} = \rho(\boldsymbol{d}^{(0)}) = 1$ at the initial state of the game. |

which is "a requirement that each individual would weakly prefer participation in the mechanism to not participating" (ibid).

The value of $\rho^{(t)}$ represents how much benefit the whole society gets from the decision $\mathbf{d}^{(t)}$. This can reflect the feature of "Efficiency", which is "a requirement that a social decision maximises the sum of utilities of the individuals in society" (ibid). However, ideally the efficiency of a decision must be checked against the preferences of all agents in the sense of Pareto Efficiency.

## REAL-WORLD SIMULATION

### *Serious Gaming Workshop*

After building the social decision game setting shown in section 2, it was first implemented it in a real-world simulation. Thirty participants took part in the game during an international workshop on 'democratisation' hosted at TU Delft, within the ITN HERILAND program. Initially, four democratisation levels have been designed as described above. However, due to the limited number of participants, only three of them (without the 3rd group setting) were successfully implemented as a real-world simulation.

The three groups faced different levels of democratization in terms of the weights and rights during the vote for the agents, thus having a different $\mathbf{w}^{[r]}$, and *ceteris paribus*.

The background information, the rules, the dynamic, and the settings of the game were explained to the participants before the game started in the workshop. The preference types of all the agents were written on a profile card given to the participant confidentially (see an example in Figure 1). They needed to read their assigned profiles and make sure they understood the game rules before starting. All participants could choose to reveal, hide, or misrepresent as much information written on their profile card as long as they obey the ONLY rule of being loyal to their mandated preference types when they voted for decisions. As is discussed in section 2, the agents' voting decision in relation to their utilities was simplified into a non-compromising non-payback strategy, i.e., do not vote "YES" for any decision $\mathbf{d}^{(t)}$ that consists of any object-choice pair $d_j$ that they are

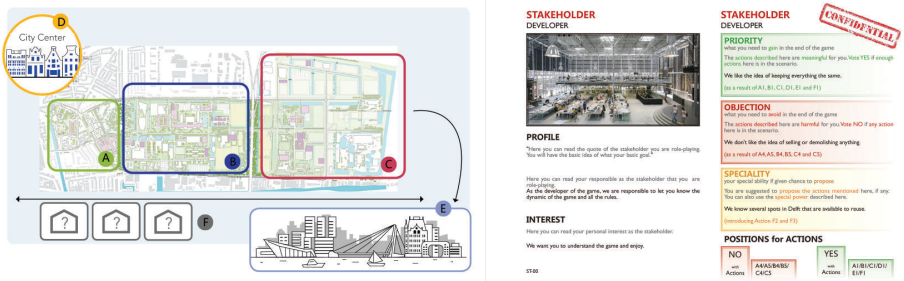


Figure 1
Example of the game interface during the workshop. Left: the sites to decide on. Right: The stakeholder profile declaring the preference type of each agent.

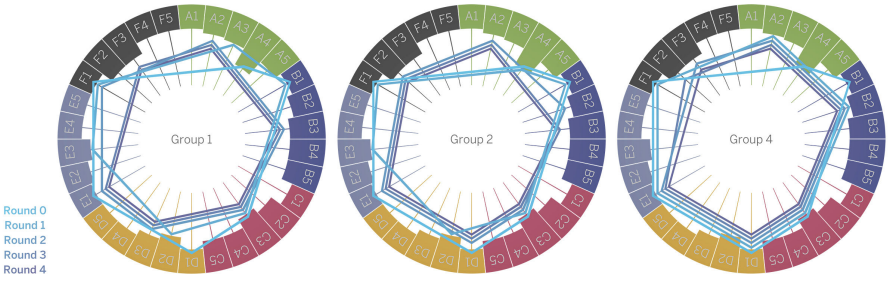


Figure 2
The decision made by each group within each group are shown as polygons, whose vertices are the chosen choices per each object (coloured groups). The height of the coloured bars indicates the potential social benefit of each choice per object. Hexagons are slightly offset inwards and coloured differently so as to distinguish different rounds of the games.

mandated to oppose to, no matter how many other object-choice pairs in the same decision are in their preference, even though that decision may lead to a higher overall social benefit.

During the workshop, a 'game master' was assigned to each group, who observes, coordinates, records, and monitors the gaming process. They made sure that all participants (agents) followed their mandated strategy and voting rules. Each group started from the same initial decision $\mathbf{d}^{(0)}$, which triggered a "NO" vote for at least one agent. They had four rounds to discuss, negotiate, and propose a new decision $\mathbf{d}^{(t)}, t \in [1, 4]$ to be voted at the end of each round.

It was stressed to all the participants and the game masters that this game had twofold goals: 1) that the primary goal for the game was to find a decision that gets a "YES" from all participants, i.e. proposing a good-enough social decision that could fulfil the requirement of "Individual Rationality", characterized as a consensus that minimally satisfied everyone involved; and 2) that the secondary goal was to seek to maximize the total gain-cost ratio of the final decision provided the consensus was already met, thus proposing a better social decision that fulfilled the requirement of "Efficiency".

Since in one of the three groups, the votes of some of the agents were 'secretly' dumped (with a $w_i = 0$), there was a special outcome, where the primary goal was reached while some agents were voting "NO". In this case, the 'excluded' agents could join forces and use a special card "FIGHT" to start a strike, which could force the others to invalidate the 'successful' outcome and resume further discussion considering their opinions. For each group $r \in \{1, 2, 4\}$ and for each round $t \in \{0, 1, 2, 3, 4\}$, the decision $\mathbf{d}^{(t)[r]} \in D$ and the voting configuration $\varphi^{(t)[r]} \in \{-1, 1\}^n$ were recorded for each round of the game for all the three groups to be used in the analysis.

### *Simulation Outcomes*

The three groups played the game under the instruction of the game masters. Almost all the participants expect for $(a_8)$ the citizen in group 1 obeyed their mandated preference types. Within the 4 rounds of game, two of the three groups (group 2 & 4) managed to reach consensus and came up with an individual rational decision d that was not opposed by any participant. The other group (group 1) also claimed to have reached consensus while $a_8$ (the citizen) disobeyed the rules and voted YES even though the decision did not completely match his mandate. Meanwhile, one of the groups (group 2) managed to reach the only feasible & efficient decision that maximized the social benefit $\rho(\mathbf{d})$. As shown later, this was very unlikely to happen if left only to chances, since only a rather small portion of the decision set $D$ would satisfy the primary goal of individual rationality (0.36% for group 1 and 2, and 3.6% for group 4, considering their different voting weights $w^{[r]}$ ). The decisions for each of the groups are plotted in Figure 2.

Interestingly, group 4 reached their "incomplete" consensus regardless of the "NO" votes from some of the participants who had a voting weight $w_i$ of 0 in

the second round already. The fact that those participants were ignored triggered three of them to initiate a "FIGHT" striking against the outcome. The group resumed the discussion and approached a complete consensus that eventually satisfied everyone.

## ANALYSIS

### *Analytic Methods*

Here, the proposed mathematical framework in Section 2 would be extended with a set of analytical methods for studying: 1) the difference of the explored decisions in each round, 2) the effectiveness of the game dynamics, and also 3) the effectiveness of the different democratisation set-ups in different groups.

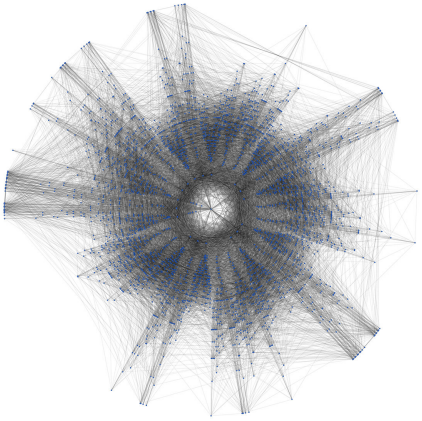

Figure 3
The embedding of the decision graph in the polar coordinate system. To create this embedding, we map the index of each decision to angular coordinates and we map the reversed social benefit of the decision to radial distance. This means that as closer the decisions get to the center of the graph, the higher their gain-cost ratio is for the society.

The first step is to enumerate the decision space and model the relations of the decisions together. Here, the decision space is modelled with as a graph $\Gamma$. Within this graph, each node represents a decision d, and each edge indicates that the nodes at the end of it differ in one and only one of their object-choices $d_j$. Consequently, the graph $\Gamma$ represents the similarities of the decisions since it is essentially connecting similar node-decisions. In $\Gamma$, each node has a degree of $m \times (l-1)$. This is because the choice of any one of the objects can be differed($m$ possibilities) and that choice can be differed to any choice except the one already existing in the decision ($l-1$ possibilities). Considering the setup of the gaming workshop, each node in $\Gamma$ has a degree of $6 \times (5-1) = 24$. Moreover, $\Gamma$ has a diameter of $m$, since traversing each edge is equivalent to changing a choice about a certain object, and it is obvious that by changing the choice of all objects, one at a time (in total $m$ times), any node-decision $\mathbf{d}^{(t)}$ can be reached from any other node-decision $\mathbf{d}^{(s)}$.

On the decision graph $\Gamma$ the graph-theoretical distance (path-length) between every two decisions can be used to measure the difference of those decisions $\texttt{dist}\left(\mathbf{d}^{(s)}, \mathbf{d}^{(t)}\right)$ (see Figure 3). Comparing the distance between the decisions of each round, it can be used to compare the extent to which a group explores the whole range of possible decisions in a game-round (cf. section 4.2 for exemplary results). This particular definition of distance makes it possible to eventually relativize the progress made in decision-making in each round of the game. To indicate such relative progress, the leap difference function $\zeta$ is defined as dividing the change in the gain-cost ratio by the distance of two decisions (cf. Table 5 for details):

$$\zeta\left(\mathbf{d}^{(s)}, \mathbf{d}^{(t)}\right) = \frac{\rho\left(\mathbf{d}^{(t)}\right) - \rho\left(\mathbf{d}^{(s)}\right)}{\texttt{dist}\left(\mathbf{d}^{(s)}, \mathbf{d}^{(t)}\right)} \qquad (3)$$

### *Analyses of Simulation Outcomes*

Firstly, the decision graph ($\Gamma$) for the game setup is formed given the objects (**o**) and choices (**c**). The preference type of voters specify which decision-nodes are consensual and which are not. Since the voters are different in each group, the set of consensual decision-nodes differ per group; and as reaching consensus is the primary condition of this game, the percentage of consensual nodes gives a rough estimate of how hard it would be to reach a consensus in this game. During the gaming workshop, group 1 and 2 had 12 consensual decision nodes, while the limited number of voters in group 4 had made a con-

| Description | Notation | Note (Example in our game) |
|---|---|---|
| A set of nodes of Decision Graph | $V = D$ | Each node is a decision $\boldsymbol{d}$ |
| Total number of Nodes | $\lvert V\rvert = \lvert D\rvert = l^m$ | $\lvert V\rvert = 5^6 = 15625$ |
| A set of edges of Decision Graph | $E = \{(\boldsymbol{d}^{(s)}, \boldsymbol{d}^{(t)}) \lvert \boldsymbol{d}^{(s)}, \boldsymbol{d}^{(t)} \in D, \lvert \boldsymbol{d}^{(t)} - \boldsymbol{d}^{(s)}\rvert = \sum_{j=1}^{m} \mathrm{abs}(\boldsymbol{d}^{(t)}[j] - \boldsymbol{d}^{(s)}[j])\}$ | Each edge connects nodes which only have one choice difference |
| The degree of each node | $\deg(\boldsymbol{d}) = \boldsymbol{m} \times (\boldsymbol{l} - \boldsymbol{1})$ | $\deg(\boldsymbol{d}) = \boldsymbol{6} \times (\boldsymbol{5} - \boldsymbol{1}) = \boldsymbol{24}$ |
| Total number of Edges | $\lvert E\rvert = \frac{\sum_{d \in D} \deg(\boldsymbol{d})}{2} = \frac{\lvert V\rvert \times \deg(\boldsymbol{d})}{2} = \frac{l^m \times m \times (l-1)}{2}$ | $\lvert E\rvert = \frac{5^6 \times 6 \times (5-1)}{2} = 187500$ |
| Decision Graph | $\Gamma = (V, E)$ | Look at figure 3 for an embedding of the decision graph for our workshop |
| Distance between decisions | $\mathrm{dist}(\boldsymbol{d}^{(s)}, \boldsymbol{d}^{(t)}) = \sum_{j=1}^{m} \mathrm{abs}(\mathrm{sgn}(\boldsymbol{d}^{(t)}[j] - \boldsymbol{d}^{(s)}[j]))$ | It is the geodesic distance (steps) of two nodes in the decision graph |
| Leap Difference Function | $\zeta(\boldsymbol{d}^{(s)}, \boldsymbol{d}^{(t)}) = \frac{\rho(\boldsymbol{d}^{(t)}) - \rho(\boldsymbol{d}^{(s)})}{\mathrm{dist}(\boldsymbol{d}^{(s)}, \boldsymbol{d}^{(t)})}$ | It is the difference of the social benefit function of two nodes normalized by their distance |

Table 5
The nomenclature of analytic methods

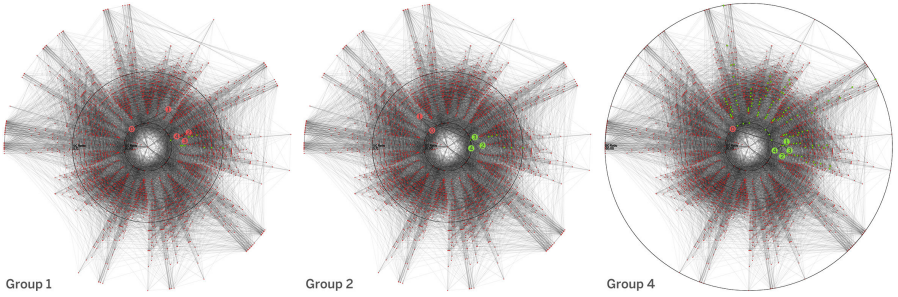


Figure 4
Green nodes are consensual decisions, and Red nodes are non-consensual decisions. Blue trajectory and the numbers indicates the progression of decision making through playing rounds for each group. Black circles highlight the bounds of gain-cost ratio for the consensual decisions.

sensus more-easily reachable and raised the number of consensual nodes to 120 (see Figure 4).

The distance function relativizes the change in rounds compared with each other, and in the whole game compared between groups. This relativization reveals the amount of exploration that has happened in rounds and groups. In Figure 5, group 1 and 2 have explored more of the decision graph compared to group 4. In addition, by comparing the gain-cost ratio of the decision of each round against the traversed distance on the graph, it shows that although all the group have started from $\rho(\mathbf{d}^0) = 10$, only group 2 has finished the game with the same gain-cost ratio.

## DISCUSSIONS

It is remarkable that that all three groups with different levels of democratisation have finally reached consensus (or claimed to have reached consensus) in the limited rounds of discussions and negotiations for this game design, as it is almost impossible to reach consensus purely searching and discovering the arena randomly, according to a brute-force computation. There must have been some strategies to learn from the human participants about how they manage to transform the information and learn from the past scenarios. However, it is arguable that the setting is only hard if the preference types of the individuals are not a common knowledge to the society

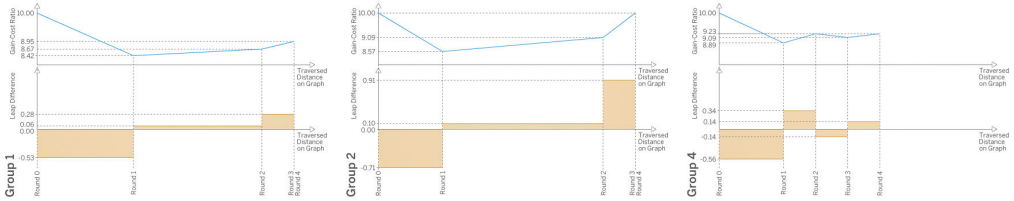


Figure 5
Blue line: gain-cost ratio plotted against the traversed distance, Orange Line: leap difference function against traversed path lengths per each round. After the "FIGHT" in the round 2 for group 4, the leap difference function becomes negative. It is also presented that the initial round of all groups has a negative value, which is due to the fact that they have started from a non-consensual node with 10, therefore their first step has been toward consensus, rather than maintaining the gain-cost ratio. Moreover, in the last round of all groups the leap function has a positive value.

throughout the game process. The initial state of this game satisfies such a requirement, where the preference profile is claimed to be confidential (as shown in Figure 1). However, any specific behavioural strategy of the participants was allowed during the discussions. If they come into a point where everyone agrees to collaborate and unveil their secret preference types, then the game is no longer a dilemma (as is also the case for the repeated form of the Prisoner's Dilemma), rather a simple puzzle to observe and solve. This also mimics the reality and implies the value of such participatory social decision game for the real-world competition and collaboration.

Future research is expected to construct an Agent-Based Simulation Model using the same game settings as described in this paper. The performance of different strategy models and voting mechanisms will be tested, including a benchmark performance with random walks. Agents can be devised to follow the strategies that is learnt from the real-world simulation from human participants and related state-of-art research. It is also promising to study the effect of changes in the proposed parameters and functions to allow more complicated social settings, which may include scenarios in which: trade-offs or compromises of certain individuals are allowed; learning and diffusion of preference types could occur; each agent represents a different number of people and thus have different weights; or majority consensus, rather than complete consensus is expected. Later the games with different settings can be tested with humans again, comparing with our computational simulation results, and teaching them to perform even better.

The eventual purpose of this research is to integrate democratization and participation into the decision-making process for heritage redevelopment and spatial planning, as is one of the essential goals of the HUL recommendation. It is also interesting to see that in our real-world simulation outcome, the group 2, where all agents could vote but only part of them could propose new ideas, reached the optimal solution most easily; while the group 4, where some of the agents are invited to the discussions but were not given the right to vote, triggered the "FIGHT" branch and started a strike in their society; and in the group 1, where the highest level of democratization was assigned and each agent could change the decision evenly, there was a great chaos during the discussion and one of the agent even had to play up to deceive the game master that the consensus was met. This is also consistent with the idea that the democracy is necessary, but among the different forms of democracy the informed consent would contribute to the most efficient democratization (McGee, 2009).

## CONCLUSIONS

The objective of the research was to frame an urban development problem as a gamified multi-actor/multi-objective social decision-making process and accordingly formulate the problem mathematically so that it can be further analyzed by means of graph theory and game theory.

The biggest question in the background of the research was whether such problems can be solved computationally (at least from a mathematical point of view), and if yes, why should they be framed as games? The answer to this question is partially de-

pendent on the scale (level of detail) and thus the complexity of the problem and to some extent on the social aspects of the problem. Our formulation shows that the order of complexity of such problems is exponential with respect to the number of objects raised to the power of a maximum number of choices available per each object. This could be a justification to apply [meta] heuristics to search for optimal outcomes. However, there may still be two reasons why both gaming and artificial intelligents methods (meta-heuristics) could be relevant at the same time: on the one hand, in case of large problems, they could be NP-hard, i.e. mathematical problems with no known algorithms for solving them systematically in polynomial time, whose solutions can only be 'approximated'; and on the other hand, even if the solution is approximated by means of algorithms and machines, humans must be involved in formulating, understanding, and attempting to solve the problem so that they can 'accept' and 'abide by' the solution (the final decisions). In other words, the didactic use of the game and its necessity for enabling participation cannot be overruled by the use of AI methods. On the contrary, the two approaches need to be combined to make the most out of such decision-making processes, socially and scientifically.

The main contribution of the paper is proposing a formal (mathematical/computational) formulation of a 'wicked-problem'. The analyses performed on the proceedings of the games show that designing such games and playing them can help diverse groups reach consensus more efficiently.

## ACKNOWLEDGEMENT

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# Smart Contracts for Decentralised Building Information Modelling

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*The paper presents a model for decentralizing building information modelling, through implementing its infrastructure using the decentralized web. We discuss the shortcomings of BIM in terms of its infrastructure, with a focus on tracing identities of design authorship in this collective design tool. In parallel we examine the issues with BIM in the cloud and propose a decentralized infrastructure based on the Ethereum blockchain and the Interplanetary filesystem (IPFS). A series of computing nodes, that act as nodes on the Ethereum Blockchain, host disk storage with which they participate in a larger storage pool on the Interplanetary Filesystem. This storage is made available through an API is used by architects and designers creating and editing a building information model that resides on the IPFS decentralised storage. Through this infrastructure central servers are eliminated, and BIM libraries and models can be shared with others in an immutable and transparent manner. As such Architecture practices are able to exploit their intellectual property in novel ways, by making it public on the internet. The infrastructure also allows the decentralised creation of a resilient global pool of data that allows the participation of computation agents in the creation and simulation of BIM models.*

**Keywords:** *Blockchain, decentralisation, immutability, resilience, Building Information Modelling*

## INTRODUCTION

### *Scope*

The paper describes a conceptual mechanism through which Building Information Modelling (BIM) applications can be developed in a decentralised environment, both in terms of the stakeholders participation and the infrastructure the software executes on. Further we implement a decentralised BIM prototype, running as smart contracts on the Ethereum Blockchain and IPFS, as validation to the concepts described. Our premise for developing the concepts and prototypes within, lie within the potential of the blockchain mechanism for identity and authorship management, immutability and resilience of data, and decoupling of the data from "cloud" infrastruc-

tures that might be used for work and dissemination. While computing "clouds" have appeared as a solution to collaboration between different design agents, the provision of centralised servers and clouds controlled by the companies that provide it, undermine data integrity and ownership

### *Context*

BIM has been praised as an end-all solution for various architectural design processes however the idealistic view of an all-encompassing tool differs to views of BIM from practice. [Holzer], echoing [Maver] and the seven deadly sins of CAAD, analyses the seven deadly sins of BIM, after critically reflecting on the uptake of computational design in practise. These are techno-centricity, where technology focus takes precedence over design process and culture, ambiguity of what the BIM spectrum might mean, elision of the information and responsibility of agents for it , hypocrisy of requiring IPD-Integrated Project Delivery as a silent twin project organisation to BIM, the delusion of asking for 2d information while requiring 3d work , diffidence - i.e. denying the need for process change where BIM is presented as an already good fit and monodisciplinary, where design exploration and design validation happen in professional silos.

### *Need*

Against this analysis the paper puts forward dBIM-decentralised BIM as a paragon of virtues that can counter-balance some of BIM's seven deadly sins. Through decentralisation , we are thus targeting the fragmented nature of the AEC industry, while providing the infrastructure for creating and adopting new business innovation and design innovation models.

## BACKGROUND

While BIM advertises a high level of integration of information, this is not the case in terms of processes. The fragmentation of the AEC industries, where integration is a new idea, is evident in the separation of processes in the industry from the brief setting to post-occupancy evaluations. For example Koutamanis [2017 ] describes the potential for integration of briefs with BIM processes and by extension how client needs can be embedded into BIM processes. In terms of working against technological fragmentation, and towards decentralised solutions, the most efficient current solution lies with BIM on Cloud. [Afsari et al] discuss extensively the opportunities and constraints that BIM interoperability in cloud-based collaboration poses. They identify that there is a knowledge and practice gap in terms of alternative technologies that can assist Cloud-BIM interoperability solutions. In parallel BIM cloud-based solutions, as discussed by Afsari et al, are developed in silos by the respective vendors, leading to vendor lock-in. They also discuss data exchange via MVD-.ifc schemas through the "cloud" where the vendor infrastructure is presented as a Software as a Service (SaaS) and Platform as a Service (PaaS) model. The discussion on cloud interoperability confines then itself to the established internet protocols, of Https, FTP, SMTP. In terms of interoperability four metrics are established: degree of interoperability, autonomy (the level of each cloud platform can work on its own, with no connection to other cloud apps), the degree of privacy of information, and the verification complexity. For example, [Almutairi et al] analyse federated, loosely coupled, and ad hoc collaborations based on these four metrics, and within these metrics the constraints of data exchange of BIM between cloud platforms are established. The constraints are related to compatible APIs, a universal data exchange format, but also the nature of the export and import of data through the APIs rather than .ifc format. Practically this means the data exchanged between "clouds" does not take place via exporting and importing in .ifc but by making specific calls to the API of each application.

Within this complexity, Doyle and Senske [Doyle et al 2019] construct a discussion on authorship, co-authorship and metadata analysing the co-dependency of designer-authors and originality on the work of others, in a sociotechnical framework that

accounts software and hardware interdependencies, for the creation of a single drawing. This interdependency, and the discussion that all authorship in design is in truth always a co-authorship fits very well with the diffusion and collective ownership and editing of BIM amongst a wide range of stakeholders, from experts to users. In this aspect of downstream users of data, Ozel [2005] discusses the confluence of BIM in the design, construction and management of buildings. The disconnect that exists between various phases of the design -construction-management in the AEC industry at the level of data. This incentivises a coordinated approach that integrates business processes across multiple phases of the lifecycle of a building project, and significant costs savings by efficient and effective use of data. Within the same paper, the challenges to achieving a uniform building information modelling approach that can seamlessly integrate data are presented: intellectual property concerns, both at the level of software and the data themselves, organisational challenges that are connected to the scale and fragmented nature of the construction industry, an incentivised AEC community, consensus on the level of the building model and where present, global aspects of BIM. How is it then that even various "cloud" versions of BIM do not completely solve the problem of fragmentation, intellectual property and design authorship, and organisational challenges of AEC projects? Is the nature of the industry such that only through a well orchestrated approach to information processing in tandem with organisational structures, design authorship (with whatever liabilities that might ensue) that BIM truly show its virtues and advantages? Within this context of challenges, we have turned to the distributed ledgers and the Ethereum blockchain as a potential data infrastructure paradigm.

## DECENTRALISATION

### *The Ethereum Blockchain*

The Ethereum Blockchain (ETH) is a universal state machine, a distributed equivalent to a Turing machine, implemented over a decentralised network of nodes, that have a mechanism of reaching consensus on their state. On the Ethereum Blockchain data is immutable, public, and the blockchain itself embeds the capability to run codes in the form of "smart contracts" providing anyone with the opportunity to use Ethereum as a computer. As Ethereum is Turing complete, ie. it does not know when a computation will halt, the concept of "Gas" is introduced as a unit to measure the computational effort to run a specific operation, and create incentives for keeping computational loads low. Additionaly, as per Turing completeness "Gas" ensures computations terminate. A further incentive to operate on the Ethereum platform is by "mining" ETH, the currency on which the platform itself is based, and getting rewarded for actively verify computational transactions by receiving ETH As any other operation, storing data in the ETH blockchain has a cost and it is quite expensive due to the fact that it provides valuable services like immutability and distribution in the entire platform. Furthermore, the cost increases for larger set of data, hence forcing operators to look for alternative solutions for data storage. Some have used cloud storage such as Google Drive, Amazon Web Services or Autodesk BIM360, building within them their own Common Document Environment for BIM usage. However, in order to keep the consistency of the decentralised infrastructure concept and overcome the analysed problems with centralised servers, we opted for combining the Interplanetary File System IPFS in tandem with the ETH blockchain. IPFS is a distributed file system that allows the sharing of files on the web without the existence of a centralised infrastructure. Again, a network of nodes participates in IPFS by sharing storage space from their computational resources, where files are copied in a redundant manner.

### *Discussion of prior work and state of the art Methdology*

Previous work by the authors [Dounas et al] have described levels of CAD integration, blockchains for optimising architectural design but also decen-

tralised autonomous organisations for architectural design, and new forms of structuring a design teams' decision-making approach[xxxx]. Our work with BIM has been unique in the sense that [Li et al] has recognised by surveying experts and building a socio-technical framework: the integration of BIM and blockchain has so far low engagement from researchers or practitioners. Other uses of the Blockchain in the AEC space include the financial incentivisation of tier 1 contractors [Kifokeris 2019 ], the management of supply chains [Qian et al, Kifokeris], the management of documents [Luo et al], the automation of billing and payments [Li et al, Ye et al], the automation of contracts between stakeholders and contractors [Di Giuda et al]. In particular, [Luo et al] mention the issue of using the blockchain as a means to verify the authenticity of a file and its authors. Within current cloud infrastructures they report the contradiction of storing the file in a centrally located and controlled server in a cloud infrastructure, while file verification and validation takes place on a decentralised distributed blockchain. As such, Ideally the completely decentralised BIM solution involves the use of a DLT and the in tandem use of decentralised storage, computation capacity and memory. The Ethereum Blockchain presents itself as a particular platform where anyone can perform computations on, and as such one could run theoretically CAAD and BIM application directly on it. However the ETH platform is expensive in terms of storage and memory, due to the replication that takes place amongst its nodes. Hence there exists the need to decentralise the underlying infrastructure (Figure 1).

### *Value in BIM collaborations*

The main goal of these strategies in collaboration in BIM is to safeguard and enhance value produced by the designers. Value then is not only added by identifying and resolving bottlenecks but is also produced in BIM by design collaboration. It would be a positive factor if we are able then to identify the pattern of creating value in design and the person(s) who created the value in a collaboration both as a responsibility and as an action. Additionally, it would enhance our understanding of BIM collaborations if we are able to identify the moment at which value is created in a collaboration, but also which part of the project in which it was created. We should then be able to identify value creation in architectural design by identifying three key aspects: the pattern of adding value, the member(s) of the design team responsible and the chronology of value creation along with the subpart of the project where this takes place. At the opposite end of value creation, [Hattabe et al] identify the pattern of error creation along with the potential benefits of lean management practice in BIM processes, which are the reduction of errors and constraining their diffusion in the team. Value proposition of tool interoperability in BIM is more widely examined by [Grilo et al], where they conclude that value creation is not just tool specific in BIM but includes culture, context, values and business practices. Grilo et al furthermore develop the idea that contractual issues in BIM interoperability and all the aforementioned issues are only partly addressed by current BIM practices, and only in homogeneous BIM environments.

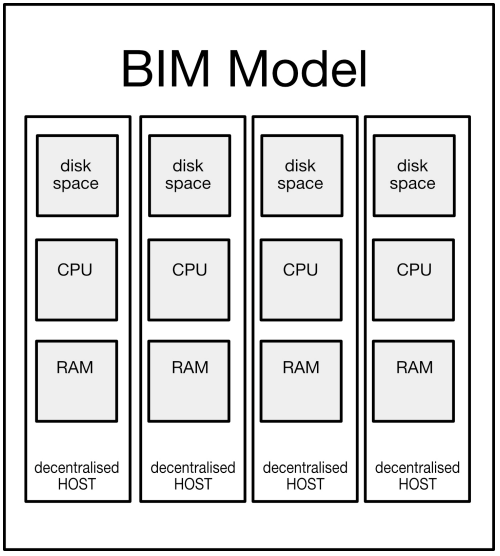



Figure 1
a completely decentralised BIM infrastructure: hosts share their CPU, RAM, Disk storage

We have employed a hybrid research method, combining an evolutionary prototype built-in software, which validates concepts in computational design. The hybridity of the method stems from using qualitative research within previous examples in literature and in parallel developing the smart contracts needed for our approach to work, and testing them in a semi-automatic manner. By using a public blockchain, the code and data used are already public on the Ropsten test network, hence accessible to other researchers to test. In relation to alternative processes, as with cloud storage, IPFS and the Ethereum blockchain work in our prototype in the same fashion as calls to a cloud API, hence the exchange of .ifc files is not needed. The advantage of course is that the computational control lies with the owners of the hardware and the IPFS space, rather than the operational administrator of a cloud infrastructure. By using IPFS and creating the smart contract on a test network one is able to validate the functionality of the prototype directly, and use this a minimum viable product to develop further decentralisation.

### *Smart Contracts*

We implement two smart contracts, one that takes care of storing the IPFS hash value, and increasing the version number of the file, hence it stores two values, an integer and a hash.

```
Code:

pragma solidity ^0.6.0;
contract dbim {
//this is a string variable holding
 ↪ the IPFS hash of the file in
 ↪ question
string public difference = "
 ↪ I_pretend_to_be_an_IPFS_hash";

//unsigned integer- this is stand for
 ↪ the version of the file
        uint public myUint;

    function setMyUint(uint _myUint)
     ↪ public {
         myUint = _myUint;
    }

    function setIPFShash(string memory
     ↪  _difference) public{
    difference = _difference;
    }

}

Code End/
```

The contract is deployed on the Ethereum test network "Ropsten" using the following transaction, with the following address. To access the contract one needs to either host a node on the "Ropsten" network or access it through a third party such as the Metamask plugin on the chrome web browser. When deployed on the "Ropsten" test network one is able to set the IPFS hash of the file they are working on, and the version number (Figure 2).

```
https://ropsten.etherscan.io/address/
0
 ↪ xaaa08fa38996dce6e2671d77a66ec0f6f01a8ec1
 ↪

0xAAA08fa38996DcE6E26
71d77a66Ec0F6F01A8eC1
```

In parallel, an .ifc file is uploaded to IPFS, it is hashed, providing it with a unique identity, and shared with all stakeholders (Figure 3). The hash of the file from IPFS is used to uniquely identify that particular instance of the file, and is stored on the smart contract, increasing the version number by one. Thus one is able to keep track of the changes to the file, verify any kind of changes by comparing the hash files of the files on IPFS with the hashes that are stored in the contract in the blockchain. To save resources in case of frequent changes a third file with the record of all hashes can also be kept on IPFS and verified via a hash on the blockchain. This allows us to essentially create a decentralised BIM environment, where files are not stored on a cloud, but on a decentralised filesystem. Thus a design team can use IPFS storage for storing all their BIM files, edit them, and record the

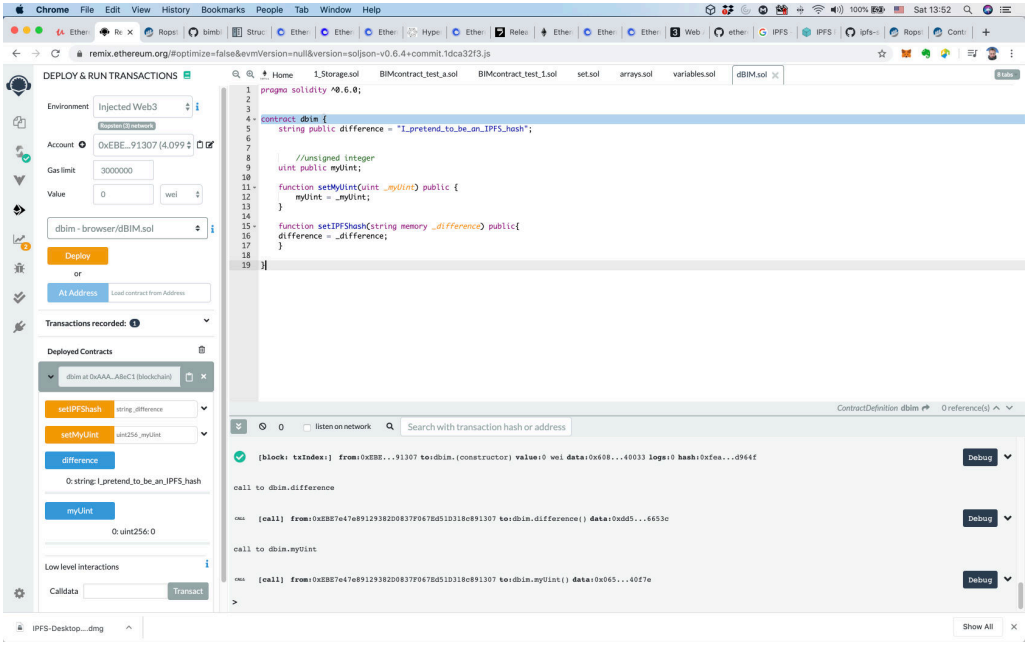



Figure 2
the smart contract that keeps track of BIM file changes, deployed on the "Ropsten" network. (by the authors)

hashes of the changes on a particular contract on the blockchain that is publicly verifiable. This negates the need for a centrally procured server in the cloud, but also cancels any kind of control that software vendors might have on the files of the users, a limitation that was recognised by Afsari et al [2017]

However a limitation exists in the number and incentives of IPFS nodes that would be willing to participate and clone the files on the IPFS common document environment that the design team creates by effectively storing files on IPFS. Thus we need to introduce incentives in the form of payments to these nodes. A complete diagram of the process is presented on Figure 4.

A similar smart contract handles the transaction for the decentralised hosts. It takes care of recording the hash values of the files stored, the time they are stored and edited, the size of the memory needed on each host for such decentralisation, and the amount of ETH paid according to the incentives formula for the platform. To be able to protect intellectual property, files can be uploaded on IPFS after they have been cryptographically secured. This might take two forms, either digitally sign them, or completely encrypt them so that the IPFS nodes can not read the files. At the same time, BIM files on IPFS with their hashes stored on the blockchain can be verified by non-expert stakeholders.

This process creates two new business models for stakeholders in BIM: the model of the hosts, i.e computational nodes that act as the infrastructure of the model and get compensated for it by the users, and the architects who can exploit their intellectual property by sharing it on such a system with the world. A particular example are BIM parametric libraries. If an architect currently releases a parametric library on the web without any protection or encryption, anyone can exploit it without difficulty. With

Figure 3
BIM file loaded on IPFS and hashed.

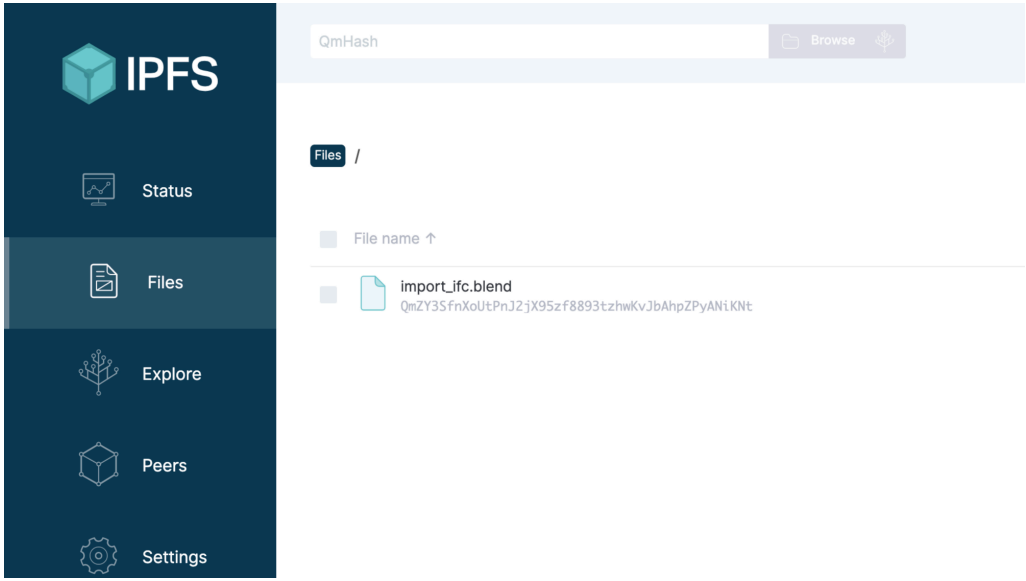
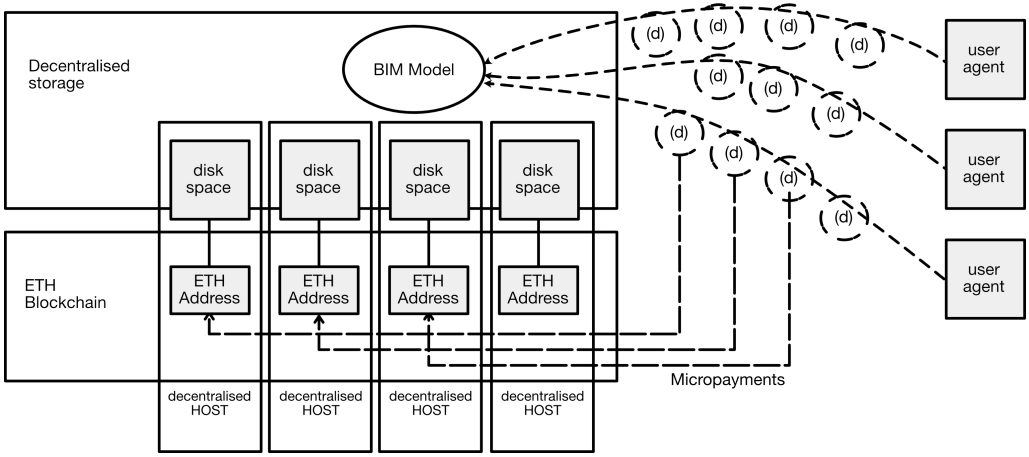



Figure 4
Diagram of decentralised storage and editing operations for BIM. (by the authors)



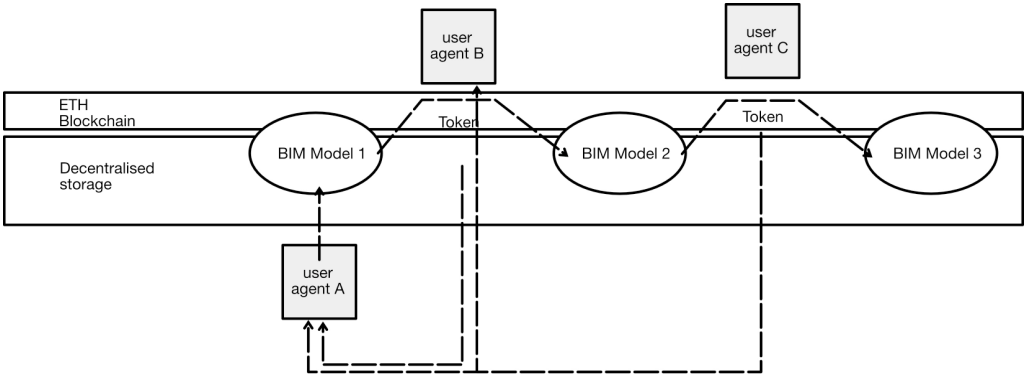



Figure 5
Incentivisation and tokenisation of BIM editing. User A creates the initial BIM file, gets assigned an initial token. User B edits and adds value, triggering a token payment fo user A, while user C edits and adds value, triggering a token payment to both user B and user A as precedent co-authors. All transactions, user identities, tokens and value created are saved in the ETH blockchain.

using the facilities of the ETH blockchain and IPFS one can host whole files and libraries on the decentralised web, allow the use and modification of such a library and ensure payment through the execution of smart contracts. Taking this concept further one is able to also create additional work on top of these libraries by editing them and reusing them in another project. As such a BIM library or file stored on IPFS will have a series of authors, all recorded in an immutable manner, and a series of connection to projects, also recorded in an immutable manner. This immutability allows the secure execution of smart contracts to allow payment to each of the creators and co-authors of each library. The difficulty and constraint there in lies in the form and ratio of the payment according to the actions and the value that each contributor to the library has created. At the computational level, we can overcome the attribution to Fiat Currencies by using tokens on the ETH blockchain, where each contributor accumulates tokens for each edit and use that takes place down the line on the library they created. (Figure 5)

This tokenisation of design action can lead to the creation of an internal economy within the decentralised Building Information Modelling application, where each user-agent and stakeholder is incentivised to maximise value for the whole ecosystem and the increase of the collective value will also increase each user's compensation. As an organisational model this shadows the processes of Integrated Project Delivery model, but provides the infrastructure, scope and scale for a decentralised and wide, global application.

## *Discussion*

The simple infrastructure we have developed poses a number of questions in terms of organisational infrastructures, ownership of this infrastructure, along with the desired balance of control versus value in the architectural design practice. In terms of production and control of information, we understand that industry 4.0 poses a number of challenges to architectural design under the lens of automation. Others [Koening] have compared Industry 4.0 processes and their automation with Cybersyn, the control infrastructure developed by the socialist government in Chile, in 1973, taking into account the embedding of information nodes directly into production. In parallel what we are proposing the embedding of value much closer to the architectural production, but also the explicit recognition of value creation through architectural design. The challenge lies of course in being able to establish and compare qualitative value in each edit of the files in an architectural design paradigm: Are all edits of a BIM file creating value? Are there specific patterns that we

can observe if we diligently record the blockchain a series of authors that edit the file in turn? Can we observe and classify such patterns and recreate them in the future? Certainly the infrastructure proposed here allows for such embedding and for such a control to be recorded. We would need a certain scale though, perhaps globally, to be able to recognise patterns of value creation. We mention a global scale, as the ambition is to have the infrastructure described here used by as many architects as possible, administered as a commons, rather than as just another tool.

## CONCLUSIONS

We have presented a set of scripts that create a proof-of-concept in creating the nucleus of decentralised building information modelling. Our prototype allows for the participation and collaboration of a decentralised design team, the creation of a shared infrastructure for common document environments, and the incentivisation of stakeholders that participate in the creation of this decentralised infrastructure. Within this infrastructure, one is also able to foresee new business models for architects and computational designers, where for example designers publish a computational design file or a BIM family/parametric assembly on IPFS, verify their authorship through the blockchain, for example a particular computational design that is valuable to others. Then other architects and computational designers take that file and edit, or use it and incorporate it into their own work, paying through the blockchain at the same time the original creator, but also any other computational designer that has edited the file. Through the blockchain we will be able to build an architecture of collective authorship, where architects are incentivise to participate and share their work because they will get rewarded. We look forward to building the software infrastructure that will make this possible.

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# Designing (for) Change

## *Towards adaptivity-specific architectural design for situational open Environments*

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*The introduction of cybernetic principles to the architectural discourse some 50 years ago stimulated a new notion of buildings as dynamic and under-specified systems. Although their traditional conception as static and deterministic objects has remained predominant to this day, concepts for adaptive architecture capable of interacting with their surroundings and occupants have gained renewed attention in recent decades. However, investigations so far have largely concentrated on small-scale applications or individual adaptation strategies. The notion of situational open Environments, as argued in this paper, provides a framework through which adaptivity can be conceived and explored more holistically as well as on an inhabitable scale. Environments reject deterministic design and adaptation solutions and hence call for integrative and interactive design strategies that not only allow for the exploration of particularly adaptable (i.e. underspecified) architectural morphologies, but also for the communication and negotiation during their further development beyond deployment. In respect thereof, this paper discusses the potentials and implications of computational (design) strategies, meaning the agencies of buildings, designers, residents, and surroundings. The presented research originates from the author's involvement in an interdisciplinary research project centered around the development of an adaptive high-rise building that incorporates various adaptation strategies.*

**Keywords:** *Adaptive Architecture, Architectural Environment, Computational Design, Agent-based Modeling, Architecture Theory, Cybernetics*

## INTRODUCTION

The notion of adaptation in architecture can be traced back far into the past, considering that already early dwellings such as tents were adapted to their respective location and situational functional requirements (Schmidt III and Austin, 2016). One aspect that has changed significantly over time, is the extent to which adaptation strategies involve the interaction between architectural systems and their surroundings, residents, and designers. Schnädelbach (2010a), for example, defines adaptive architecture as buildings "that are designed to adapt to their environments, their residents and objects as well as those buildings that are entirely driven by internal data". He thereby implies the active involvement i.e. agency of buildings in adaptation processes.

Historically, adaptivity was conceived more passively and solely user-oriented, -operated and -initiated. Contrary to Schnädelbach's definition, buildings were not designed to adapt but to be adapted. This applies both to traditional Japanese architecture, which enables residents to reprogram interior spaces through lightweight furniture and sliding partition walls; as well as to modernist architecture, which synthesizes the former concept with highly under-specified und program-agnostic 'open-plan' building systems.

In the 1960s, the introduction of cybernetic principles to the architectural discourse (Pask, 1969) allowed for a shift in the conception of adaption from adaptability to adaptivity. At that time, the concept of architecture as feedback-based system stimulated a new understanding of buildings as dynamic and active environments with agency. It challenged the prevailing view of static and passive material objects, including their design and operation.

In more recent decades, primarily facilitated by technological advancements, concepts for 'cybernetic' architectural environments experienced a renaissance. The discourse has expanded towards a broader scope, involving notions such as interactive (Fox, 2016), responsive (Kroner, 1997), robotic (Kapadia et al., 2014), flexible (Kronenburg, 2007) and smart (Van Hinte et al., 2003) - most of which Kolarevic et al. (2015) summarize under the umbrella of 'architecture of change'. Despite the ubiquity of digital and physical computing, most explorations so far have focused on small-scale experimental structures, or on extensions to established building systems, such as adaptive façades or motorized building elements.

Given the acceleration of today's demographic and environmental transformations, the concept of adaptivity as a strategy to address uncertainty gains in significant relevance. This, however, requires adaptation to be conceived, explored, and realized more extensively as well as at a full architectural scale, which not only poses technical challenges, but also substantial conceptual, methodological, and ethical ones. This paper discusses these challenges and possible approaches from the perspective of (computational) design as well as through the lens of (architectural) Environments, their design and situational open development after deployment - based on the authors' previous, current, and future research.

## ADAPTIVE ARCHITECTURE

Adaptive architecture and its interdependencies with residents and surroundings can be thought of comprehensively within the framework of Environments. In art since the 1960s, Environments have questioned our relationship to objects - traditionally perceived as non-subjects - both conceptually and spatially with regard to context, initiative, authority, ethics, and aesthetics. Artists have conceived Environments as open situations to create a space for happenings and interactions based on collective and playful encounters and thus to reappraise the relationship between the natural and the social environment. Kaprow's Environments offered actions and choices to visitors, such as throwing objects or moving furniture, through which he aimed to establish a more direct relationship between object (art) and subject (visitor).

By extending the spatial and conceptual borders of artworks, Environments question the idea of the modernist (art) object and the role of artists

and viewers in its production and perception. Yayoi Kusama developed her environmental approach from several years of painting biomorphic forms in an almost obsessive repetition. She covered entire spaces, humans, plants, and animals with her motifs (above all with dots) through which she aims to interconnect and collectivize people and things to dissolve the distinction between self and other, subject and object, animate and inanimate.

It is therefore no surprise that the ambitious Fun Palace project was initiated by the theatre director Joan Littlewood, a pioneer of improvisation, with a program for an interactive, situational, and participatory theatre space (Herdt, 2017). In 1961, the architect Cedric Price designed its open steel-gridded structure with flexible and adaptable interiors, relative openness to the exterior, and various accesses. The design of the adaptable structure, comprising hanging rooms, moving platforms, escalators and fixed stair towers, aims to foster dynamic interactions with its visitors and their movements. The underlying organizational principle for direct interaction was developed by a cybernetic committee, led by Gordon Pask, in view of the city, the building and its visitors. (Herdt, 2017). Together they developed the Fun Palace as an "environment ... suitable to what you are going to do next ... An indeterminate participatory open-ended situation". (Banham 1969). The adaptable, interactive, cultural, and educational complex as a "laboratory of fun" remained unbuilt, yet it constitutes an early example of an architecturally conceived Environment. Open-ended and joint development processes, as intended by the Fun Palace, stimulate a continuous and mutual exchange between users and building, also involving the domain of city and landscape.

With the shift from predetermined objects towards dynamic and open-ended situations, our conception of buildings, the tasks of architects and the roles of residents change significantly. A brief review of adaption strategies in contemporary architecture reveals ecological, technological, and social dimensions.

Adaptive buildings exhibit dynamic behaviors in response to changing conditions of users or surroundings in real-time. This includes reactions in their structure, space, façade, shell, furnishing, interior qualities, and differ with respect to their actuation (e.g., passive, manual, active) as well as in the immediate and overall purpose of adaption and timespans.

Architects initially think of spatial and user-oriented adaptation. Steven Holl's Fukuoka House invites its residents to turn and fold three walls of their apartment, allowing for the transformation of a conventionally divided space into an open one. They might also think of Shigeru Ban's elongated Naked House, similar to a greenhouse, in which family rooms constitute movable cubes that allow for the creation of numerous spatial arrangements. Similarly, ECO-29, an event room by FoxLin and Brahma Architects, enables a variety of spatial scenarios through the transformation of an interior membrane by means of motors and pulleys (Fox, 2016). The ExoBuilding at the University of Nottingham presents a continuous real-time adaptation of a flexible architectural envelope in response to the movement of yoga practitioners and their breathing based on real-time audio data. The immediate adaptation of the space-defining shell enhances the user's posture, concentration, and serenity (Schnädelbach et al., 2010b).

While these adaptation concepts focus on flexible architectural spaces and the well-being of occupants, other buildings show adaptations to changing environmental conditions. Depending on wind and sun conditions, for example, the kinetic façade elements of the Al Bahr towers in Abu Dhabi open and close partially to reduce radiant heat inside the building (Hill, 2018). Others leverage material properties for actuation purposes, such as the HygroSkin Meteorosensitive Pavilion developed by the Institute of Computational Design (Correa, 2013). Thin bi-layer wood composites open and close in response to humidity and thereby provide adaptive ventilation and shading.

Adaptation can also shift built boundaries, when in the Sharifi-ha house in Tehran by Nextoffice an entire room rotates outwards; or temporarily dissolve boundaries, when the roof that covers the Starlight Theater in Rockfort opens up to the sky. Traditionally immovable architectural elements are becoming increasingly flexible. This includes the ultralightweight SmartShell developed at the University of Stuttgart, which features three hydraulic supports to compensate for static and dynamic load cases resulting from wind or snow (Sobek, 2016). With the introduction of actively adaptive supporting structures, one of the last notions of inflexible architecture has been overcome. Although these examples primarily show only a single adaptive response (of space, structure, façade, envelope, interior quality), they indicate altogether future dimensions of adaptivity that architects will design, and residents will interact with.

### *Towards adaptive architecture in situational open Environments*

The selected projects show various objectives of adaptive architecture: on a global scale, ultralightweight construction saves resources, materials and (embodied) energy; on a local scale, adaptive buildings respond to their immediate surroundings to maintain their stability, reduce radiant heat or manage energy; and at the same time, they adapt to their occupants by providing flexible spaces, comfortable room qualities or lighting conditions. However, adaptive behaviors are often predefined and only allow for a certain range of actions. Therefore, in view of the open development of adaptive architecture and its residents, adaptation scenarios must be integrated both holistically and in-deterministically. Moreover, one-sided architectural adaptation to surroundings and residents does not offer sufficient openness and flexibility, which in turn calls for the active participation of residents, who interact with the building, actively participate in its development through the pursuit of their individual or collective interventions.

In this scenario, various adaptations to the surrounding, the building and its residents are part of an open and situational development process in which architecture and actors are in a continuous exchange and negotiation. These technological, architectural, and social dimensions of adaptation can be conceived through the concept of Environments. Following the artistic and architectural Environments of the 1960; their condition changes dynamically and continuously. Adaptation in Environments is not limited to architecture but takes place on all sides in the form of social, natural, technological and architectural adaptation processes in a broad context such as community, city, climate, therefore serving as a mediator between the local and the global (Ulber, 2019).

At a first glance, adaptive buildings that dynamically adapt to their surroundings and residents gradually realize cybernetic visions and utopias of the past. First cybernetic approaches with a closed system concept, on the one hand, are problematic for adaptation in situational open Environments with changing priorities. This also applies to their regulatory processes. Homeostatic systems balance all inputs as they strive for an ultimate equilibrium state, in turn preventing open-ended development. Cybernetic systems of the second order, on the other hand, are extended by the role of the observer and can therefore be regarded as self-reflexive by questioning goal and purpose (Yiannoudes, 2016). Nevertheless, the larger context (city, society, climate, crises) is not sufficiently dynamic and relationally negotiable, as in the case of adaptive architecture in Environments. Adaptation based on feedback loops might also lead to one-sided amplification: For example, with maximum user comfort being the goal, repercussions of climate change might be enhanced, or social adaptation scenarios prevented (Ulber, 2019).

The concept of Environments goes beyond the cybernetic notion of input-output. Rather than focusing on the conception of buildings as machines, it allows to conceive adaptivity more radically and thus helps to overcome traditional boundaries and distinctions. It aims to enable open and dynamic de-

velopment processes with new forms of communication and interaction.

The authors' participation in the Collaborative Research Center 1244 "Adaptive Skins and Structures for the Built Environment of Tomorrow" at the University Stuttgart [1] provides a comprehensive framework for examining the architectural dimension of Environments at an inhabitable scale. The CRC 1244 currently realizes an adaptive high-rise building (Figure 1) which will integrate various adaptation strategies, including an adaptive supporting structure comprising adaptive truss- and surface elements, adaptive interiors as well as different adaptive façade systems.

Figure 1
CRC 1244 Adaptive high-rise building at the University Campus in Stuttgart, Germany (Source: ILEK, University of Stuttgart)

Given the involvement of 18 institutions with researchers from the fields of Art, Architecture, Computational Design, Civil Engineering, Aerospace Engineering, Energy Engineering, Mechanical Engineering, Systems Engineering, Building Physics, Computer Science, Material Science, Life-Cycle Analysis and others - the implications and complexity of realizing adaptivity at the intended scale and extent becomes evident. Within this interdisciplinary group, research focuses on a broad spectrum of questions ranging from form-finding (Fröhlich et al., 2019 ), actuator integration (Weidner et al., 2018 ), control strategies (Wagner et al., 2020 ) and system safety (Ostertag et al., 2019 ).

Architectural design plays a central role in this context, as is integrates the above domains and their requirements into the articulation of inhabitable spaces. It mediates between the object (the building) and the subject (occupants), while the notion of Environments increasingly challenges their distinction. Compared to conventional design processes, multifaceted and open-ended adaptation does therefore not only call for a profound extension of protagonists and objectives during the 'design phase', but also an extension towards the subsequent period of inhabitation i.e. the 'development phase'. This requires the reconsideration of established approaches to design, in particular with regard to methodology and agency.

## CONCEPTION & DESIGN

Adaptation in Environments as an open-ended development along with ever-changing internal and external boundary conditions implies both situation- and context-specific temporal dynamics that eventually lead to a change of a building's state or behavior. Consequently, architects are required to shift from designing static and deterministic objects towards complex and dynamic Environments.

With this shift, design parameters and objectives that have so far played a minor or no role in (early) architectural design gain in significance right from the outset. Not only does this involve the definition of adaptation scenarios including their respective actuation, sensing, communication, and interaction strategies, but also the exploration of particularly

adaptable architectural and structural morphologies beyond established typologies. However, the notion of adaptability by no means refers to the optimization towards highly specified adaptation goals or performances. On the contrary, it means their underspecification i.e. the building's ability to respond to conditions and requirements beyond those assumed or anticipated at the outset. In doing so, adaptive architecture is enabled to unfold indeterministic behaviors informed through the interaction with its surroundings and occupants, as opposed to merely executing predefined routines.

Similarly, Van Hinte et al. (2003) argue for "an open-ended condition to start from rather than a final condition to arrive at" because "the more we look ahead, the greater the chance that we're wrong. So whatever is projected and built should allow either for easy modification or a change of program [...]." The challenge of designing adaptive architectural systems can thus be seen as a twofold one, given the necessity of developing technologically and architecturally advanced design solutions being both goal- and purpose-oriented as well as to some extent -agnostic. This duality inherent to the design of complex yet open-ended systems correlates with Pask's (1969) definition of a "Simple Cybernetic Design Paradigm", in which he emphasizes that both goal and purpose of a system "may be and nearly always will be underspecified, ie, the architect will no more know the purpose of the system than he really knows the purpose of a conventional house." To facilitate such processes, the authors' research focuses on developing integrative methods and computational tools that support the design (i.e. design space exploration) of adaptive architecture for open Environments.

### *Towards interactive design processes*

Previous research has shown the inadequacy of state-of-the-art (information-)modeling tools in the context of adaptive buildings. This relates to their inability of incorporating the abovementioned design objectives, as well as to their limitations regarding the representation of dynamic building characteristics (Ernst and Menges, 2018). Consequently, not only adaptivity-specific approaches to design but also adequate methods and tools by which their architectural opportunities can be explored and implemented are necessary. Computational design presents a strategy to support and to navigate such processes, which, by no means, can be considered intuitive or trivial. Nevertheless, given the qualitative dimension of architectural design, the relationship between architects and computers must be an interactive, collaborative and symbiotic one (Licklider, 1960). Contrary to drafting and modeling-oriented tools that are available to architects nowadays, a design instrument, as pursued here, provides the basis for computationally augmented design processes, as envisioned in Pask's design paradigm (1969).

Agent-based modeling (ABM) constiutes a computational strategy that is particularly suitable in this context, as it provides a means to explore the emergent phenomena of complex systems (Macal, 2016). It thus facilitates the interactive exploration of dynamic (building) behaviors that emerge from the definition and manipulation of local design rules. Consequently, ABM provides designers with insights into the intricate correlations between geometry, topology, materiality, and adaptability.

To investigate the applicability of this strategy in the context of adaptivity, ABM is currently employed in the author's ongoing research on the design of adaptive buildings, which to date, is focused on the design space exploration of adaptive truss structures. The conception of load-bearing structures as adaptive systems aims to significantly reduce required construction material through the strategic manipulation of occurring deformations and forces within the system by means of sensor-actuator mechanisms (Sobek, 2016). For this strategy to be effective, truss systems call for a geometrical and topological layout that particularly facilitates such manipulations. Here, this characteristic is referred to as 'adaptability'. Given that established structural typologies only exhibit a low degree of adaptability (Steffen et al., 2020 ), the

exploration of adaptivity-specific morphologies is of both environmental and structural but also of architectural relevance.

Within the CRC 1244, researchers developed a method to evaluate local and global adaptability characteristics of a given truss system (Geiger et al., 2020 ), which serves as crucial design feedback. Data is computed and stored in the form of topology-specific matrices that describe the degree to which each structural element is capable of manipulating the others. When applied to a full architectural scale with 2000+ structural elements, adaptability matrices contain up to four million entries or more (Figure 2). Linear design approaches based on trial and error are therefore neither feasible nor effective. Contrary to black-box optimization strategies (Wortmann , 2017), ABM enables designers to directly i.e. interactively engage with such high-dimensional design information that would otherwise be inaccessible (Maierhofer and Menges, 2019).

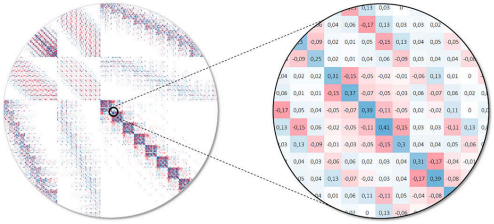

Figure 2
Adaptability matrix of an adaptive truss structure comprising 2000 truss elements (Source: ICD, University of Stuttgart)

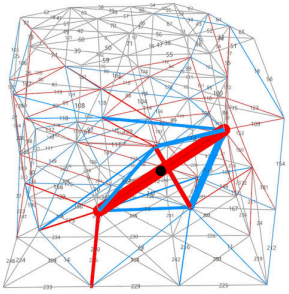

Figure 3
Adaptability visualization: Impact range of element X (Source: ICD, University of Stuttgart)

In the case of the abovementioned authors' research, agents represent truss-nodes, whereas a relationship between two agents defines a truss element. Local matrix values (Figure 3) are dispatched to the corresponding agents and translated into agent-behaviors i.e. design rules. In doing so, important design information can be encoded into the adaptive design model, which in turn represents an interface for the interaction between human and machine. In other words, it allows for the synthesis of computational and human design agencies and thus for the integration both of qualitative and quantitative design criteria. Through intuitive design actions, such as defining geometric design constraints or explicitly moving, deleting, and adding building elements, designers can thereby comprehend resulting building behaviors based on the dynamic response of the self-organizing design model.

Even though current research is focused on the design of adaptive truss structures, it lays the groundwork for future research on the integration of more extensive and heterogeneous adaptation strategies. Moreover, it demonstrates a methodological avenue for identifying the breaking points between specification (i.e. predetermination) and under-specification (i.e. adaptability) in view of the primary design of architectural Environments receptive to situational specification and open development later on.

## DEVELOPMENT & ADAPTATION

Open adaptation processes in Environments mean a continuous development with temporal dynamics of at first underspecified designs. Subjects of adaptation that have at first been vague and ill-defined become increasingly clear, and with it, the specific goals, and purposes of previously merely anticipated adaptation scenarios. Consequently, the primary design phase is transferred to a development phase, involving the building, its residents, surroundings and hence their (actual) needs, demands and behaviors. This constitutes a design shift from the digital to the material world - from virtual to real. In addition to the situational curation of preconceived reactive adaptation strategies, an open-ended and col-

lective development phase must as well facilitate the pro-active adaptation of the building itself, i.e. its reconfiguration and extension, as a response to changing requirements, not only within but also beyond its (under-)specified state.

To unlock the opportunities of open-ended adaptation processes, deterministic architectural morphologies and predetermined control trajectories must be kept to a minimum, as such would constrain situational developments informed by real-time data, feedback, interaction, and negotiation. To accommodate for transparency and democracy throughout such processes the protection of privacy and sensitive user data must have the highest priority and the possibility of comprehending building behaviors as well as direct intervention by the users must be facilitated at any moment in time. Moreover, AI-based control and decision making should be regarded critically, as there are indications that excessive monitoring and suggestive system behaviors lead to the conditioning of user behaviors (Yiannoudes, 2016). A prerequisite, however, is a shared means by which common and conflicting interests in Environments can be communicated, negotiated, and translated into situational design solutions.

### *Towards participatory adaptation processes*

Adaptation based on situational requirements allows for real-time and collective design explorations (i.e. adaptations) of deployed architectural Environments through the participation of occupants, as previously demonstrated by 'Self-Choreographing Network' (Maierhofer and Soana et al., 2019). The project presents a self-aware robotic structure that exists and performs at the interface of the computational and physical space (Figure 4). It is capable of changing its spatial state based on cyber-physical interactions that involve computational processes, elastic materials, embedded robotic agents and human occupants. From a conversation between structural requirements, environmental conditions, user behaviors and design intentions emerges a continuously evolving architectural Environment. Through user-operated changes of the system-topology, alternative spatial choreographies and conditions can be explored in collaboration with the self-aware structure. Its digital instance, in turn, not only mirrors and informs actions in the physical space in real-time, but also provides a shared interface for virtual design experimentations that are safe, unconstrained, and free from consequences.

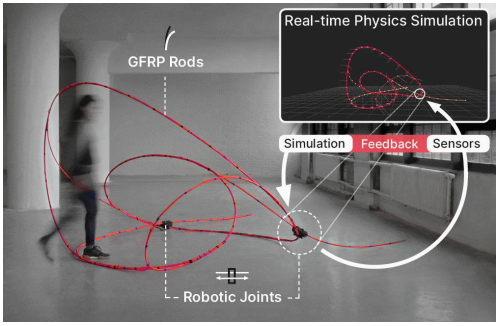


Figure 4
Self-Choreographing Network (Source: M. Maierhofer & V. Soana - ICD/ITKE, University of Stuttgart)

On a larger architectural scale, this strategy could offer a resident community the opportunity to collectively explore, evaluate, refine, and test various adaptation scenarios as well as their local and global implications. In participatory processes of this kind, residents can communicate and negotiate their ideas, for instance, when it comes to redefining common areas, when spatial needs of individual tenants change or even when the whole building requires reprogramming. Supposedly 'optimal' solutions proposed by the digital system, however, may stimulate and inform such processes but entail the problem of automation bias, which would potentially neglect or even prevent valuable user initiatives. Therefore, new communication and interaction strategies are a prerequisite to ensure genuine resident participation and to provide them with the agency to actively shape their Environment collaboratively, democratically, and responsibly.

A prototypical interface for such processes is currently being investigated through the augmentation of three-dimensional spaces with the afore-

mentioned agent-based design instrument as well as through the translation of sensor-actuator values into agents and agent-behaviors. This is to establish an immersive and shared cyber-physical space that connects the building, its resident community, and surroundings (i.e. the Environment) both virtually and physically.

On this basis, Environments, that have so far expanded the spatial and conceptual boundaries within the field of art, questioning the idea of the modernist (art) object and the role of artists and viewers, now - in the context of architecture - allow us to redefine tasks, responsibilities and roles of all actors involved (building, residents, designer, surrounding). By inviting the viewers to immersive experiences, Environments - according to Kaprow - enable the self-reflective engagement of all participants. With the emphasis on "process over product", rigid Western dualisms (subject-object, nature-culture, architect-inhabitant) are challenged in favor of a holistic non-binary approach.

## CONCLUSION & OUTLOOK

Adaptive architecture, when conceived in situational open Environments, can serve as an inclusive catalyst for mediation and development within and beyond its materialized boundaries. The concept of Environments provides a framework for the integration of adaptation strategies that have previously been explored in isolation and implemented in a predetermined manner. Environments invite their residents to engage in the continuous development of the spaces they inhabit.

This goes beyond enhancing user-comfort or energy-efficiency through kinetic building elements and the idea of choosing "...preferred solutions from a set of possible solutions" (Bier, 2016). Instead, it presents a promising strategy for providing the built environment with an architectural, social, and environmental robustness required for an increasingly dynamic and diverse world - in other words - it allows to design (for) change.

Above all, designing for change calls for a change in the way adaptive architectural systems are designed. In order to avoid predefined building behaviors that are unreceptive to unforeseen i.e. situational requirements. This means, on the one hand, that a buildings ability to adapt and be adapted indeterministically (i.e. adaptability) must be incorporated as a new design objective throughout the primary 'design phase'. Ongoing research into the design space exploration of adaptive truss systems represents a first attempt to investigate design methodologies for the architectural embodiment of adaptability, for which ABM represents a particularly adequate strategy.

On the other hand, design processes are to be extended beyond the deployment of their subject to provide a shared interface for situated design and decision-making during the 'development phase'. The adaptive high-rise building described in this paper will offer an experimental platform for interdisciplinary research into the potentials of situational, participative, and open-ended design processes, in particular with regard to the modes of communication, interaction and negotiation therein.

## ACKNOWLEDGEMENTS

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# Methods for the Prediction and Specification of Functionally Graded Multi-Grain Responsive Timber Composites

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*The paper presents design-integrated methods for high-resolution specification and prediction of functionally graded wood-based thermal responsive composites, using machine learning. The objective is the development of new circular design workflow, employing robotic fabrication, in order to predict fabrication files linked to material performance and design requirements, focused on application for intrinsic responsive and adaptive architectural surfaces. Through an experimental case study, the paper explores how machine learning can form a predictive design framework where low-resolution data can solve material systems at high resolution. The experimental computational and prototyping studies show that the presented image-based machine learning method can be adopted and adapted across various stages and scales of architectural design and fabrication. This in turn allows for a design-per-requirement approach that optimizes material distribution and promotes material economy.*

**Keywords:** *material specification, responsive timber composites, machine learning, robotic fabrication, building envelopes*

## INTRODUCTION

The cost-intensive and high mechanical complexity nature of the adaptive building envelopes of the past years, shifted the designer's interest towards exergy-based (Valero et al, 2010) active material systems. However, current studies (Holstov et al, 2017; Foged and Pasold, 2015, 2016; Wood et al, 2018) focusing on the architectural application of wood-based responsive systems, rely mostly on one material's phase characteristics. This in turn shows few limitations regarding the upscale of the system's performance, the steering of the highly anisotropic behavior of wood, as well as the prediction of the material's fatigue after several activation cycles and its implementation into the design process. These challenges incite research into new material practices that deploy differentiated properties, and enable response to varying design criteria, within one and the same material structure (Miyamoto et al, 1999). This shift from understanding the materials not as inert receptacles for an imposed form but rather as active agents in its genesis (DeLanda, 2004), positions the making of functionally graded materials (FGM) for site and use specific architectural applications, as central means of design material thinking. Equally concerned at the scale of material, the element and the structure, the

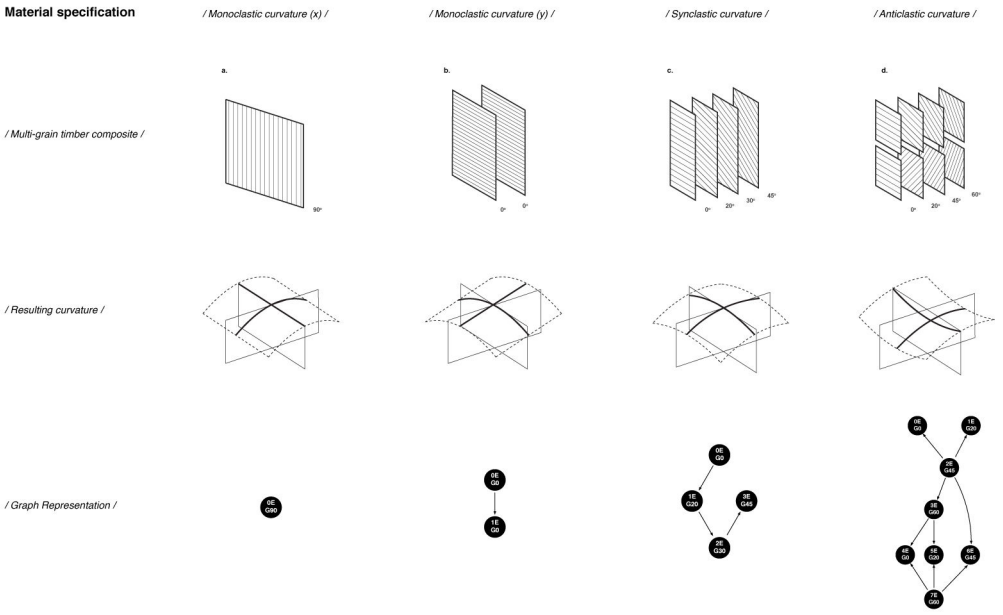



Figure 1
Material specification of FGM: Multi-grain timber composite configurations, thermally active responsive bending performance and graph map representation of the assembly topology.

authors of this paper discuss new methods for the prediction and specification of functionally graded wood-based responsive building composites, using robotic fabrication. The aim of this paper is the identification, development and advancement of a new circular design integrated workflow employing Machine Learning (ML), in order to predict fabrication files defined by specific performance and design requirements. Through an experimental case study, it explores how gradual material layering deposition of oak veneer elements with various grain directionality can allow for local control of bending stiffness and direction. Moreover, the enquiry devises how these composites can contribute to the development of a more robust thermal responsive material system. The experimental case study examines how ML can be used to train a model in order to predict and steer the heterogeneous behavior of high-resolution multi-grained timber building composites, interfacing high fidelity with low-resolution data, as well, as how this workflow can be integrated into architectural design and fabrication as an aspect of sustainability. Lastly, by using thermal responsive timber composites as a framework for material thinking, the paper discusses new trajectories and projections on future fabrication paradigms for lighter, material-driven architecture that can adopt and adapt material behavior in an architectural building scale.

## FUNCTIONALLY GRADED RESPONSIVE TIMBER COMPOSITES

Functionally Graded Materials (FGM) hold a profound place in architectural design and construction, due to their potential of displaying differentiated properties across a wide array of scales. This enables them to respond and being materially- efficient in a very refined manner to the design parameters they encounter

(Miyamoto et al, 1999). The ability to design, synthetically engineer and fabricate such high-resolution functionally graded timber composites, provides the capacity to compute and execute a behavioral response triggered by environmental conditions (Figure 1). This design framework appears to be incredibly promising, as it increases the product's structural and environmental performance, enhances material efficiency, promotes material economy and optimizes material distribution, allowing for up-scale of the material system (Oxman, 2010). However, programming a system response at the material level requires an in depth understanding of the reciprocities between the morphological implications, the behavioral characteristics and the interaction with environmental dynamics. This in turn, calls for development of material-driven computation strategies that incorporate a range of design, fabrication and actuation parameters. Previous studies by the authors (Fragkia and Foged, 2020a, b) have concluded with a series of critical parameters for the specification and steering of high-resolution and material-efficient timber composite assemblies, driven by material-environmental properties and interactions, from material, design and fabrication perspectives.

### *Material experimental studies*

**Anisotropic behavior.** As a natural fibrous composite, wood possesses a variety of complex properties and ingrained responsive capacities, related to environmental conditions of temperature and humidity, allowing for embedding sensing, actuation and regulation within the material itself. Its anisotropic dimensional behavior lies on its anatomy and it is directly related to the fiber direction. However, while the grain pattern can act as a visual indicator of the direction of bending, the prediction and steering of the veneer's movement can become challenging, due to the heterogeneity of samples in fiber directionality.

**Thermal activation.** Due to its high thermal expansion coefficient tangentially to growth rings, wood transfers thermally activated dimensional changes into responsive bending behavior. The speed of actuation, as well as the magnitude of curvature are directly related to material layout, as they decrease with increased thickness. However, in order to achieve consistent responsive behavior, rigorous control over temperature stimulation in relation to time is required. Excessive or uneven distribution of heat across the grain can lead to uneven distribution of strain and can consequently result in micro structural damage of the material composite (plastic deformation).

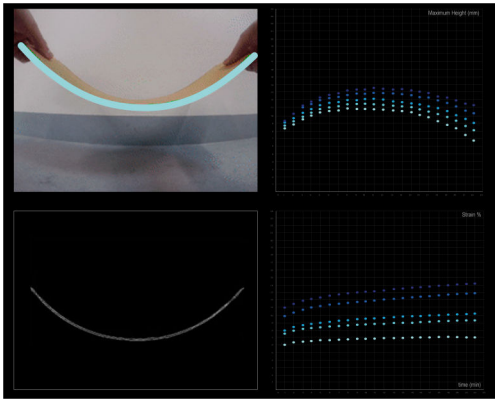


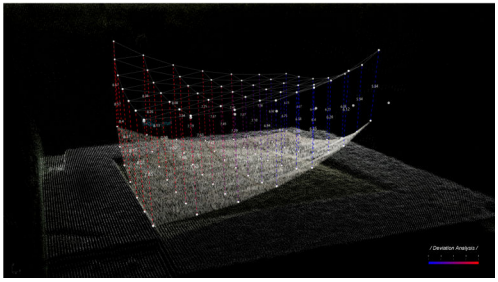
Figure 2
Object Tracking and Bending Ratio Detection using Linear Hough Transform (LHT) in OpenCV. Exporting quantitative data of max bending ratio and strain of 0.6 mm oak veneer after 5 activation cycles.

**Material fatigue.** Moreover, overexposure of the system's responsive elements to UV radiation along with multiple activation cycles can cause material decay. Such behavioral inconsistency can lead to overall reduction of the system response in terms of degrees of openness, directionality and reversibility of the dimensional changes occurred due to thermal stimulation.

### *Digital Experimental Studies*

**Predictive Modelling.** Designing for and with heterogeneous responsive FGM requires the emergence of new design integrated workflows. These should not only entail high-resolution simulation of the system's ingrained material capacities, but rather form a predictive modelling workflow of the system's behavioral shifts and inconsistencies, due to its interaction and stimulation by environmental conditions.

**Distributed Simulation.** Previous studies by the authors (Fragkia and Foged, 2020 a) provide a wide range of adopted and adapted simulation strategies, employing Computer Vision and Evolutionary Algorithms. These simulation workflows question a linear progression from design to analysis but rather calculate and combine results of different levels of precision and fidelity. In that way, they allow for parallel computational frameworks of material information, geometric configuration, structural and environmental performance to handshake (Figure 2).



**Cyclical Design Workflow.** Enabling a continuous and interactive loop between various levels of information, geometric resolutions, scales and calculation methods, such adaptive simulation frameworks allow for bi-directional exchange of information between physical and digital design environments (Figure 3). Thus, they introduce feedback and cyclical thinking as central means of responsive material design thinking.

### *Fabrication Experimental Studies*

**Dimensional Limitations.** Along with the material and design challenges, steering a system's responsive behavior in a material level includes a series of critical parameters that need to be tailored during fabrication process. The limited size of oak quarter-cut veneer sheet that the research employs, with a range from 400 to 1200 mm in width, becomes a primary material constraint, directly affecting the operational area and the scale of the design elements.

**Environmental Control.** Material calibration is directly related to the environmental conditions and therefore, the same control that is being carried out through activation must be maintained through fabrication process. Thus, it is required diligent measuring of the ingrained Moisture Content of wood, as well as control over relative temperature and humidity levels during production. This allows for maintaining consistent responsive behaviors between the reactive elements of a system.

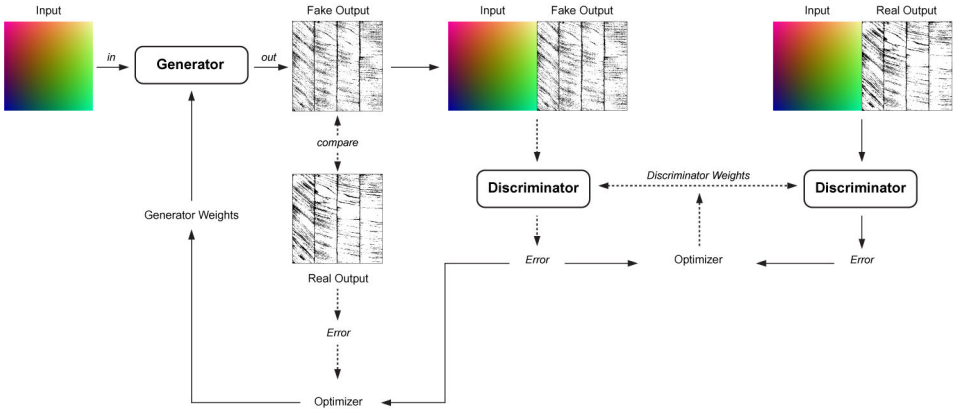
**Binding Methods.** The authors have carried out extensive research (Foged et al, 2019) on different synthetic adhesives for thermal responsive composites, including acrylics, bonding materials and structural glues, positioning the shear modulus as primary parameter for a suitable lamination. Additionally, alternative binding methods have been tested within the experimental material studies such as sewing and snapping, allowing for fast assembly and disassembly, as well as reuse of the functionally graded multi-grain timber composites.

Figure 3
Deviation analysis between the digital simulation and the 3d scan of a thermal responsive multi-grain timber composite bending performance .

## IMAGE SYNTHESIS WITH CONDITIONAL ADVERSARIAL NETWORKS

As Architecture finds itself in an era of increasing demands of predictability and performance of its outcomes, the emergence of ML approaches and its integration into architectural design practices for better leveraging data-rich environments and workflows, becomes increasingly promising (Tamke et al, 2018). Artificial Intelligence provides an intellectually attractive paradigm for the exploration and development of design processes. However, the problem of representation in design (Gero, 1991) where coded representation needs to be able to be decoded in different ways in order the design semantics to be interpreted and evaluated by both the designer and the machine, remains challenging. To address this problem, the research uses Conditional Adversarial Networks (cGAN), a branch of deep neural networks (DNN), in order to predict and steer the performance of high-resolution material composites, using low-resolution data. Previous studies in architectural de-

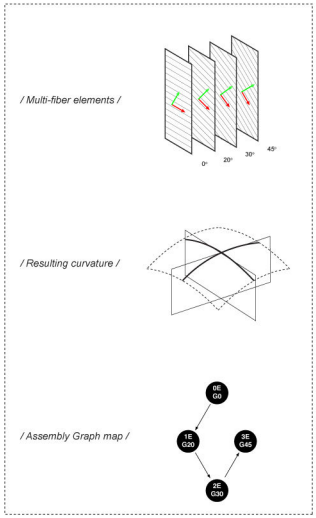
Figure 4
Architecture of the generator (G) and discriminator (D) of the cGAN model.




sign have applied DNN for adaptive fabrication processes (Nicholas et al 2017, Brugnaro et al 2017) and cGAN for textile specification (Thomsen et al, 2019) drawing recognition (Huang et al, 2018) and Wind Flow Approximation (Mokhtar et al, 2020). The presented case study employs cGAN in order to predict fabrication files that solve complex 3d configurations of responsive functionally graded multi-grain timber composites, linked to the environmental performance of a building active thermal adaptive envelope (Figure 4). cGAN models are trained in existing images where they learn to discover the essence of data and find the best distribution to synthesize it (Huang et al, 2018).Training is achieved using two neural networks trained simultaneously through an adversarial process, a Generator, that creates images that look real and a Discriminator that evaluates these data for authenticity. The process reaches equilibrium when the Discriminator can no longer distinguish real data from fake. Among many image- to-image translation applications of cGAN, the research employs a Tensorflow implementation of pix2pix supervised learning method for image synthesis (Isola et al, 2018). The method demonstrates a great potential and ease of adoption for architecture, by employing paired pixel images as training input and output. These data can be directly interpreted, produced, evaluated and imported into the design process, without the need for parameter tweaking or readjustment of data representation and structure, after training.

## PREDICTIVE MATERIAL BEHAVIOR DESIGN METHODS

Through an experimental case study, the research employs a circular workflow, intending for application from material up to the system scale, where a set of simple prototypical material composites of various grain directionality are used as training data for the algorithm. The composites are being produced through robotic fabrication and activated using a climate-controlled environmental chamber. The heterogeneous grain pattern together with the thermal responsive behavior of the composites, expressed as multi-directional bending, form the training input for the generative model. Moreover, the bend-



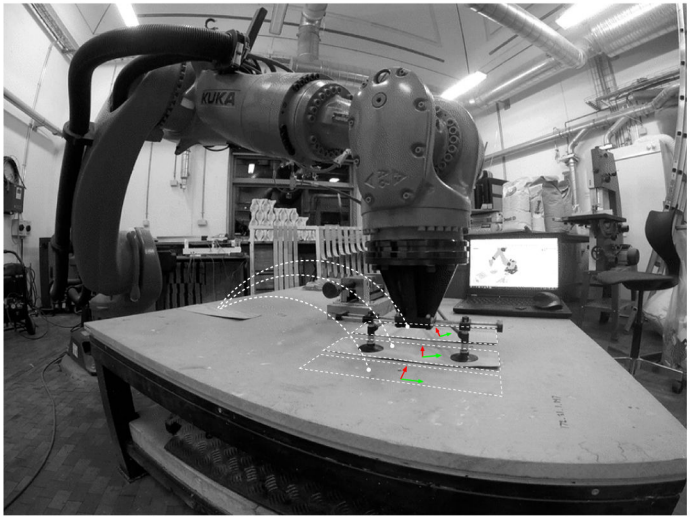




Figure 5
The robotic fabrication of multi-grain responsive timber composites is formed as gradual material layering deposition of various grain directionality, using a custom robotic end-effector.

ing performance of the composites is being real-time tracked and implemented into a design-integrated high-fidelity simulation framework, through which training outputs can be validated.

### *Fabrication Setup*

The present enquiry employs a customized robotic fabrication process for the development of high resolution functionally graded responsive timber surfaces. This process is formed through gradual material layering deposition of various grain directionality fibers, allowing for local control of bending stiffness and direction (Figure 5). The presented case study uses quarter-cut oak veneer 0.6 mm for its high thermal expansion coefficient tangentially to growth rings ( aT =11,9%), its high material strength (E=343 Nmm2 ) and homogeneity of samples, presenting an almost linear grain topology. Moreover, the presented methods are being applied in material samples of 300 x 300 mm, forming responsive elements of a greater assembly. In this design-to-fabrication workflow, the detection of the grain pattern becomes critical factor, as it represents the information needed for defining the robotic path coordinates and consequently specifying and steering material performance. This is achieved through a robotic ''pick and place'' movement, planned as a repetitive trajectory between the material stock of various grain oak veneer elements (picking) and the target point of the final assembly of a multi-grain timber composite (placing). For the classification, clustering and distribution of the oak elements within the topology of the greater architectural responsive surface, a custom robotic end effector was developed. Using pneumatic suction caps, with an adaptive operational area for elements between 10-110 cm long and the ability to transform from linear to rectangular configuration, the setup is open to various scales and material layouts. In the presented prototypical method, binding is not integrated within a single end effector but occurs as a post fabrication process, in the form of local customized PLA snap joints, allow-

ing for fast assembly and disassembly of the components. After fabrication, the multi-grain composites are being tested in a custom designed climate control environmental chamber. The climate conditioning is provided by a thermal radiator of 1000 Watt, an ultrasonic humidifier, as well as relative and surface temperature and humidity control units. For the presented study, the conditions for activating the fabricated composites were programmed with the use of temperature and humidity sensors, as well as Arduino micro-controller, maintained at 38 °C Relevant Temperature (RT) and 30% Relevant Humidity (RH), for all material experiments. The climate controlled setup allows for the material composites to undergo several activation cycles under consistent conditions, ensuring accuracy in the results.

### *Training Data*

The grain pattern of the prototypical functionally graded multi-grain responsive composites and their corresponding bending behavior, after thermal activation, form the basis for training the neural network. In order to produce training data that are readable and easy to manipulate for both the designer and the machine, we developed a Grasshopper workflow, employing Computer Vision (Bradski et al, 2011) for image processing and analysis. For this enquiry, we use Open CV computer vision library and specifically Linear Hough Transform (LHT) method for grain detection as well as real-time object tracking of the responsive composites bending behavior. LHT is a voting process aimed to detect the existence of a line within a certain class of shapes in the pixel space of an image, by assigning to each pixel the parametric equation that describes a line (Duda et al, 1972).

The collected data from the grain detection are in the form of 2d lines, while the data from tracking the bending performance of the responsive composites over time are in the form of arrays of 3d points. Each array represents an analyzed video frame and thus it directly relates the bending moments with the temperature gradient. These points are then deconstructed and remapped to RGB values in relation to their XYZ values, resulting to a unique gradient 2d color map that represents the 3d geometric configuration of the corresponding composite. This tracking method is of dual importance: On the one hand, it provides us with extensive information at the level of the material that can be easily imported into any design simulation environment and thus allow for high fidelity simulation of material performance. On the other hand, allows a bi-directional exchange of data between physical and digital design environments of the design chain. In that way, it contributes to the development of a material database, where qualitative (grain pattern) and quantitative data (deflection) can coexist and be used as training data for a predictive modelling workflow, without the need of producing huge amounts of physical tests. In this study, we demonstrate a wide range of shape changing grain patterns, resulting in various bending behaviors. In order to validate the trained model, the enquiry depicts three designed patterns resulting in monoclastic, synclastic and anticlastic curvatures respectively, which represent three different cases of the functionally graded composites performance.

### *Data Processing*

The conditional model relies on conditioning an output to an input. In this context, the training data for the neural network is based on images of a color gradient 2d map (training input) that corresponds to the bending behavior of the responsive composite after activation at 38 °C and images of the detected grain direction in the form of 2d lines (training output). The training input and output are merged together and readjusted into RGB images with constant pixel count of 256 x 256 pixel (Figure 6). The consistency of training the model for translating one possible representation of a scene into another requires sufficient training data. For that reason, we created a data set of 400 paired images, directly developed and exported through the Grasshopper workflow and trained the neural network for 200 epochs. The datasets were trained using kaiming weight initialization, batch size of 32, and initial learning rate of 0.02 with scheduled

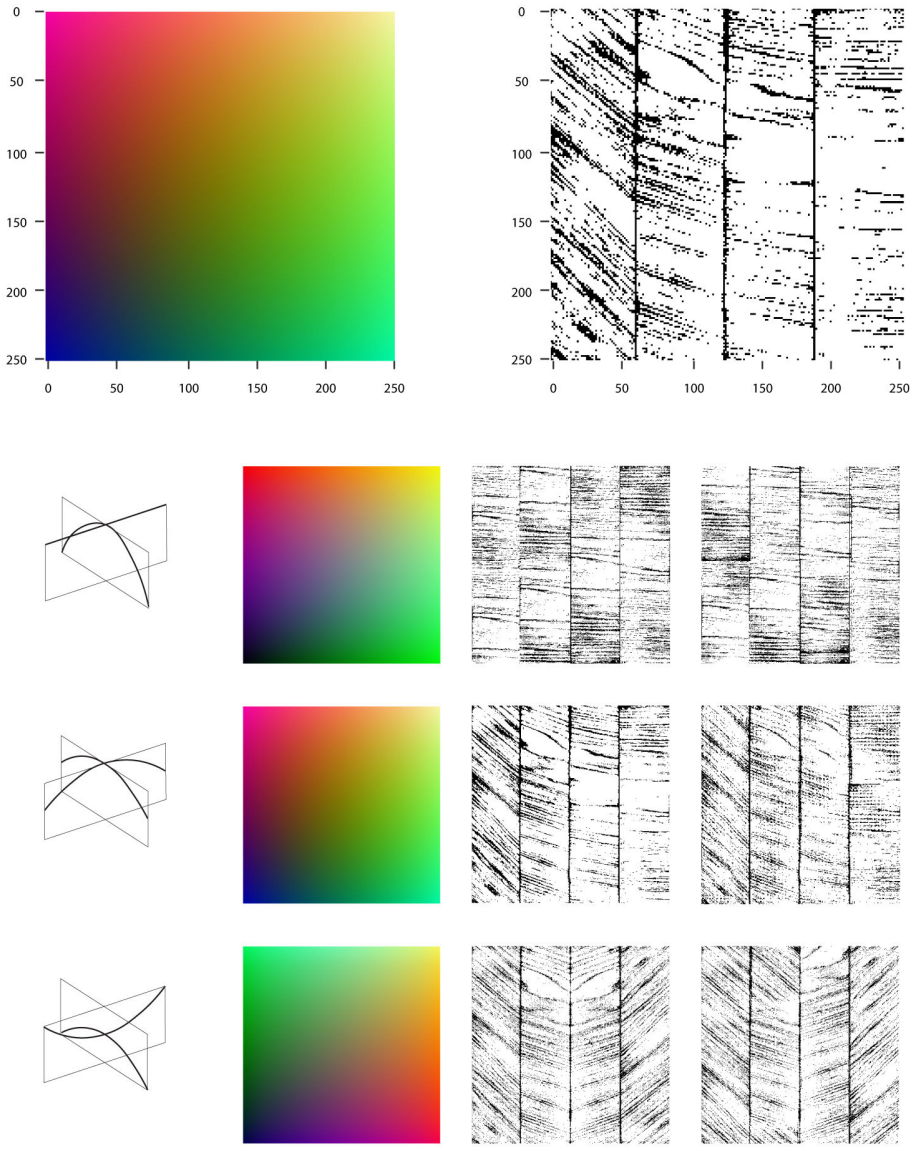



Figure 6
Paired data of oak grain pattern and gradient color map, representing bending performance of the responsive composite. Test of trained generative model for monoclastic, synclastic and anticlastic curvature. Gradient color map(training input), grain pattern( training output), generated grain pattern (learned output).

linear learning rate decay after 50 epochs. In order to monitor the progress of the training, the trained weights were saved every 5 epochs. The training duration was approximately 15 hours and was conducted on a Windows hardware configuration using Quadro P2000 GPU and NVIDIA's Cuda parallel computing platform. Following this process, we use the trained generative model, to predict fabrication files based on desired material performance, expressed as multi-directional bending. The learned output is used as input for the Grasshopper workflow, where it is being analyzed and validated.

## RESULTS

The enquiry presents design-integrated methods for high-resolution specification and prediction of functionally graded multi-grain responsive timber building composites, using ML. While the presented case study focuses on the scale of building material composites, the proposed method can be applied in a bigger architectural scale for the prediction and specification of a wider assembly of responsive composites, developable into thermal responsive building envelopes. The experimental case study proves that the use of FGM can contribute to the replacement of mechanically activated wood-based systems, due to their ability to deliver build- per- requirement material performance, linked to predefined design criteria. Connecting ML to fabrication is an opportunity to rethink the sequential relation between design information and design materiality, where the aim is not precise replication, but higher levels of flexibility, adaptability and integration. The experimental case study proves that the implementation of ML and particularly cGAN method within architectural design can be adopted and adapted since it is image-based and thus, multi-scalar. Moreover, the idea of image-to-image translation through predicting pixels from pixels makes this a common framework that could be used in other aspects of the design process, as well, such as the thermodynamic and structural analysis in relation to the dynamics of material bending performance. Finally, collecting data of sufficient size can be challenging in the field of Architecture, especially on applications of ML within material behavior and fabrication process. However the intersection between ML and high fidelity simulation that the enquiry employs, allow for production of adequate training data linked to performance criteria, directly from the design simulation environment.

## DISCUSSION

### *Limitations*

The presented method using ML algorithms for the production of fabrication files in relation to specific design requirements can be used in different parts of the design process and across various scales. However, some applications of the algorithm are highly tailored to the particulars of a given design problem. Particularly, the presented dataset has been trained for a great variety of grain topologies but for a unique wood type and thickness, 0.6mm oak veneer. In order to implement ML tools effectively within architectural design of adaptive material systems, further work needs to be developed regarding the encoding of information of different classes such as material thickness, material layout and grain topology within one pixel-based color map. This careful tailoring of training data will also allow addressing various adaptive envelope scenarios within the same workflow. Thus, the immediate limitation of the workflow is that it cannot be entirely generic. Finally, further steps over the training of the model and the precision and variation across the samples used as training data needs to be conducted, since the fidelity of the trained model relies mostly on the resolution of the simulation that is being used as the design framework for the development of the training data.

### *Perspectives*

The presented design integrated method shows the potential of establishing a parallel predictive design framework that links sense (qualitative) data and performance (quantitative) criteria across various domains of architectural design such as structural analysis, material fatigue and thermodynamic perfor-

mance. Moreover, along with the multi-grain material deposition of oak veneer elements, the paper speculates on future fabrication paradigms and architectural applications of multi-material composites that could introduce new hybrid properties. Finally, the enquiry projects on ML design integrated methods in order to predict and steer the collaborative performance of intrinsic material driven response behavior, paired with micro-controller unit driven systems.

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# D2.T10.S2. ROBOTIC TECTONICS, AUTOMATION AND INTERACTION

# Traditional Knowledge on Modern Milling Robots

## *How CNC-joinery machines promote a renaissance to lost techniques in the profession of a carpenter.*

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*The profession of a carpenter is changing significantly. Over the last 20-30 years, CNC-joinery machines became ready to penetrate the market and lead to a significant optimization of daily processes in these firms. In this case study, we take a closer look at the working techniques of a carpenter in the Bregenzerwald. This skilled craftsman found a way, of how to translate his expert knowledge on to a CNC-joinery machine. Instead of only following modern, simplified construction methods, he tried to revive historic methods and developed a way to translate his expertise. By scaling up on a technological basis, he was able to reintroduce the so-called `Dovetail joint' and by that managed to erect the first proof of concept, a single-family house. This research shows, how a new integrated robot enables a way of manufacturing, that otherwise might not be affordable anymore. Benefits of this approach can be seen on a variety of economic and ecologic aspects. As mentioned by the carpenter, these results are encouraging, but for him, the real advantage is the increased empowerment to skill, craft and knowledge typical for his profession.*

**Keywords:** *robotic fabrication, carpenter, renaissance, knowledge, tradition, wood construction*

## INTRODUCTION - CRAFT AT A CHANGE

In central Europe, the profession of a carpenter can rely on a rich and long-lasting history of at least 4000 years (Gerner, 2002). Even though the overall description of these experts on wood almost remained to be the same, the field of activity covered by a carpenter has changed. A continuous stream of technological innovation could be observed. Gradually a change of the former labour-intensive manual work progressed towards a 'machine supported wood craftsman'.

In this paper, we are going to take a closer look at one specific way of joining wood and by that illustrate a process of translation between men and machine in the environment of a carpenter. The so-called 'Dovetail-joint' was a typical and frequent way of joining wood, already used in ancient times. While this seemingly simple connection only consists of a pin and a tail, a high level of precision is crucial when

manufactured. Craftsmen have to gain a significant skill and develop a material-specific knowledge to develop appropriate solutions.

At the beginning of the 19th century, the industrial revolution gave these needs a turn. The industrial rise of nails, steel brackets and other metal fasteners made this labour-intensive way of joining wood expire (Schindler, 2009a). Besides these developments on a material basis, the upcoming science of engineering promoted structural calculations towards a more frequent use of steel parts (Polónyi, 2014). These economic and structural developments fostered a slow but steady vanishing of the 'Dovetail'.

## PROGRESSION OF CNC-JOINERY MACHINES

Since the early 1980s, a turn in wooden manufacturing can be seen. Digital tools promote a faster and more accurate production of wooden constructions. While the very first joinery-machines gave an increase on manufacturing time and precision, a raise in construction complexity could be observed since 1990 (Jeska, Saleh Pascha, & Hascher, 2015).

Even though the industry might already work with robotic manufacturing since the late 1950s (Heßler, 2014), a real starting point of CNC-robots in wooden workshops could be observed from 1989 on. According to the self-claimed world market leader in 'CNC-joinery machines for wooden workshops' (Figure 1), it was the first time that CAD-files were directly sent from a computer to a joinery machine (Hans Hundegger AG). As a direct response to a personal request, the Senior Sales Manager, Wolfgang Piatke of Hans Hundegger AG could provide a deeper glimpse. Until 2020, the Hans Hundegger AG shipped approximately 3000 CNC-joinery machines (P8/P10/K1/K2 and ROBOT Drive). Their core business can be seen in the European Union with only a few deliveries to North Amerika. For Piatke the diverse business area of CNC-joinery machines can be explained due to a wide variety of different workshop structures. These structures range from a small family-business (primarily in GER, CH and AUT) to large production plants (North Amerika) (Piatke, 2020). The company is able to cover a broad spectrum of different technological needs, aligned to the individual requirements. However, further research in the ongoing research project shall be invested to collect more data on these application characteristics.

Figure 1
Hundegger K2i working on a Dovetail (Hans Hundegger AG, p. 21); These robots represent affordable and ready-to-use solutions for a carpenter workshop. Even though they optimize issues like precision, speed and complexity of the manufacturing process, they definitely change the workflow and skill of a carpenter.

These technological advantages establish a new basis for the reintegration of wooden connections. While these wood-wood joints were to labour intensive a few decades ago, CNC-joinery machines now operate fast, precise and at a fraction of cost compared to manual work. As described by Jeska et al. (2015) this new application of 'old' wooden connections does not only replace steel connections and increase aesthetics in architecture; it furthermore has to be understood as a renaissance of traditional manufacturing techniques with a sense of novelty.

Similar approaches to translating historic knowledge into a modern way of manufacturing were already conducted by Gros (1993), Brugnaro and Hanna (2018) and Klein (2015). By developing a new interpretation of the 'Ulmer Hocker' (originally designed by Max Bill, in 1954) Gros (1993) showed, how a design classic can be interpreted in a modern production language (Figure 2). As part of his research, Klein (2015) showed how the craft of Irish crochet could be adopted to a 3d printer which leads towards a new, more contemporary interpretation of textile craft. The final presented 'Incunabula Dress' does not aim to imitate historic designs but progresses towards a new aesthetic of crochet. Klein (2015)

translated the intelligence of knitting instead of just repeating shape and form. Recording the human movement when carving a piece of wood and afterwards translating these actions on to a robot were investigated by Brugnaro and Hanna (2018). Their research showed a way of applied 'machine learning' based on human craft, that leads to a variety of craft-inspired design solutions. As finally pointed out by Brugnaro and Hanna, further research needs to be done towards new developments considering the knowledge transfer between 'human' and machine'.

Figure 2
C-Hocker by the 'NEWCRAFT' cooperation (Gros, 1993); This stool can be seen as a modern, technological reinterpretation of the 'Ulmer Hocker' designed by Max Bill. Even though the size, geometry and function remained the same, the final delivered product does represent a different appearance than the original design.

## METHODS

In this ongoing research project, data was collected by conducting an interview with Berchtold (2020). This interview frames the first position in the ongoing research project. As next steps, it will be supported by further expert-interviews, participatory observations and qualitative data sources. Being an experienced carpenter, Berchtold is running a carpentry in the region of Schwarzenberg, Vorarlberg. He and his company (including his employees, machines, etc.) will be treated as being one case. As described by Kumar (2019) a case study can be conducted as 'in-depth explorations' that will provide deeper insights into a topic. Information was gathered through observations in the workshop, an analysis of their webpages and by conducting an interview with Berchtold. Due to his unique background, his valuable knowledge and his years of experience as a carpenter, Berchtold can be seen as an expert on the topic of wooden constructions, especially on the manufacturing processes of wooden structures typical for his region.

In this paper, the results will be interpreted in accordance with Actor-network theory (ANT). This theoretical and methodological approach shall help to develop a deeper understanding of the constantly changing relationship between human and technology (Belliger & Krieger, 2006). Arguing in the way of Latour (2006), the presence of technology transforms/translates its surrounding fundamental. Considering these thoughts, it can be said that a carpenter who now owns a CNC-joinery machine, is a different Carpenter than he was before (not only just because of scaling up on a technological basis). The new technological opportunities extend the range of possible solutions, but on the other side cause an unavoidable transformation of the characteristics that were formerly implied by this craftsperson like craft, skill, perception and so on. Following the argumentation of Latour, borders between 'men' and 'machine' start to blur gradually. A strict separation between 'human' and 'technology' can/could never be drawn. Equipped with these new, physical and digital extensions, the craftsperson now ought to be described as a 'CNC-joinery-carpenter' illustrating a more up-to-date image of this craftsperson. At some point, the machines we operate, the technology we make use of, defines what solutions we are able to offer and implies how we work, inferring what the final product will look like. On the other hand, the machines themselves represent a structure, an accumulation of sensors, actuators and programs that were designed by engineers and designers with the intention to support craftspeople in the very best possible opportunity. The final developed product, in this case, a CNC-joinery machine, will only offer as many solutions, as the construction-team was convinced to imply. Wooden connections that were used infrequently on a manual basis are very unlikely to be translated into the machine program. Therefore, these options will not reappear on the CNC-joinery machine. Possible

solutions a craftsperson might have been able to offer, are then out of reach.

This permanent moment of translation, affects both, object and subject, leading to a continuous process of transformation in the perception/profession of a carpenter and the supporting technologies. This research shall provide another position in the continuous discussion concerning the evolution of human-machine interface, or more precisely state an additional perspective to current research trends (Figure 3).

Figure 3
Men and machine - working together (Schwarzmann, 2019); This image illustrates the current situation of a carpenter and a robot, working together on one piece of wood. The historically rooted profession of a carpenter therefor does undergo a significant change, concerning its way of manual work

## RESULTS

*'Well, the times changed, the demands changed [...] once, there came a time when craftsmen didn't find the time to make a wooden connection anymore. Everything that was left was a straight cut, a steel bracket and some screws'* (Berchtold, 2020).

Following this quotation of Berchtold, a little frustration concerning the profession of a carpenter in the 21sth century can be heard. Similar observations were noticed by Schindler (2009b) who named the steel nail as the end of any manual skill by craftspeople. Induced by his perceptions, Berchtold decided to establish a different approach towards his moral concept of a modern carpenter. For Berchtold, three core values had to be fulfilled to meet his demands of craft:

1. **Cost: The result has to be affordable.** As described by Berchtold, a wooden construction has to be affordable for an average client, with an average project and budget. His new approach shall be an option for all kind of future projects.
2. **Regional resources: Construction material has to be regionally available.**The primarily used building material has to be available in a radius of about 20-40 km. Due to the fact that the workshop of Berchtold is located in a rural area with nearby forests and sawmills, the utilization of industrial engineered wood (CLT, glulam timber etc.) was rejected. To meet the guidelines for insulation, statics etc. large pieces of solid timber (single pieces of solid wood, 30x30cm in cross-section) were chosen. Manipulating these huge logs does require specific skills and knowledge when being dried and processed.
3. **Craft: Construction has to meet his definition as being authentic to the profession of a carpenter.**As defined in the short quote above, the craft inherited by a carpenter did change over the last decades. The concept of Berchtold is characterised by his unique regional surrounding, his cultural network and his own definition of craft. For him, the profession of a carpenter has to be more than just erecting wooden constructions, in the most efficient way. Economical decisions and a constant longing for optimisation transformed the job of a carpenter. Furthermore, in Austria, every company has to educate young craftspeople. Therefore, Berchtold felt responsible to teach these 'craftspeople of the future' on a broad variety of construction methods.

Following these three core values, Berchtold found traditional log construction to fit best for his demands. This way of erecting a building can rely on a rich history and therefor provide numerous examples. Especially the corner styles of a log building (dovetail, tooth-edged joint, saddle notch etc.)

Figure 4
Close-up of final erected Corner 'Wertvollhaus' (Berchtold, 2004); Even though it was manufactured on a 'CNC-joinery machine', the final presented corner does look like a historic solution. Only on the inside, changes concerning the fabrication with a round milling tool would be observable. Later on, a wooden cladding will protect the corner from environmental impacts.

seemed to rise a challenge, worthwhile conducting for him.

*'Why can't we just take a way of constructing a building that did proof for the last 300, 400, 500 years. Something ... where we know what we are talking about ... and just translate it to meet today's needs!'* (Berchtold, 2020)

Since a few years, the workshop of this carpenter owns a 'Hundegger' CNC-Joining Machine. Even though the machine comes with a bunch of pre-programmed dovetail-solutions that might fit for a simple log building, these solutions miss some crucial details concerning structural and functional needs. As described by Berchtold, these pre-programmed dovetails did miss, for example, a so-called 'wind comb' (in German, transl. 'Windkamm').

At first glance, these details might not look important, but as described by the carpenter, especially these small details did prove to be essential additions when dealing with massive pieces of wood. Figuring out this lack of knowledge in a pre-programmed solution, he got into contact with the machine supplier 'Hans Hundegger AG' and started to elaborate on an improved version of their 'corner-dovetail'. With his carpenter knowledge, Berchtold convinced the 'Hans Hundegger AG' towards an optimised solution while the company took charge of all technical issues concerning the CNC-machine. As a result of this joint venture, a traditional dovetail, translated into the language of a modern CNC-joinery machine was developed. Even though the modern solution did look slightly different (due to the milling tools characteristics like round corners on the inside, instead of sharp ones etc.), the 'intelligence', the structural behaviour and the material optimization of a traditional connection could be reintegrated (Figure 4). Later on, the exterior corners will be covered with wooden cladding.

Equipped with this new Dovetail-solution, Berchtold could fulfil all three predefined core values. To give the first proof of concept, the carpenter could erect a single-family house (Figure 5). As concluded by him, the success of this project was only possible due to the extensive implementation of his CNC-joinery machine in combination with their expertise.

*'[...] starting a new project right from the absolute beginning, that's what filled us with pride and confidence. Well ... these days [when erecting a building by hand] were exhausting, but they [the craftsmen] could see the whole work from another perspective, in some kind of... as we did it a hundred years ago. [...] these challenges, that is where you really can develop your personal skills.* (Berchtold, 2020)

Even though a CNC-joinery machine did most of the processing steps, the final project does meet his definition of wooden construction, built by a carpenter. As described by Berchtold, this way of erecting a building is only slightly more expensive than compared to a cross-laminated wood construction (CLT). When comparing the overall building cost to a CLT-construction, the increased cost tend to rise for about 1-2% of the whole budget. In this case, the client was willing to get a building made from regional wood and therefore had to spend an additional 7.000€.

Figure 5
Carpenter building a log house from solid wood beams in 2019 (Berchtold, 2019); The wooden construction of this single-family house was erected in less than one week. Berchtold mentions that the same building would have taken them at least four weeks to produce if they would have worked without a CNC-joinery machine.

## DISCUSSION

*Why not imagine a unified design and fabrication process based on a series of conversations between men, designers and workers, and machines, computers and robots?* (Picon, 2014)

Following the argumentation of Picon, the ongoing debate on digital transformation in craft has to be seen as a broader discussion between all involved 'Actants'. When asking the question whether a carpenter/human or a machine/robot built this house, an answer might sound like 'none of both, but only both of them'. Arguing in the line of Belliger and Krieger (2006), a machine has to be interpreted as a partner, not as simple 'tool'.

Currently, a lot of research is being done towards new implementations of robots in construction processes. These projects, mainly fostered by architects, designers, engineers etc. could benefit from the experiences possessed of craftspeople and the people who operate these machines on a daily basis. These people own deep and rich knowledge, acquired in uncountable spent hours of working and reflecting on the material/result and therefore might be able to deliver valuable insights.

In this case-study, the carpenter did make use of knowledge, unique for his profession and was able to translate it to a contemporary technological solution. With his insights, he managed to innovate a poor pre-programmed dovetail that is regularly shipped with a CNC-joinery machine. His desire for improving an unsatisfying solution motivated him to translate his expertise and hand it over to a machine supplier who then rearranged the technological circumstances (Figure 6).

The carpenter (together with the machine supplier) managed to translate his knowledge into a language that can be understood by the CNC-joinery machine. On the other hand, the machine enabled new opportunities that the carpenter otherwise could not offer anymore. Only if the carpenter understands, how to translate his knowledge into a form that the machine can handle, an appropriate solution will result. Therefore both involved 'Actants' (the carpenter and the CNC-joinery machine) had to find a way to communicate, a mode of translation, to interact with each other. As a result, this mutual approximation does unavoidable influence the 'craft' of a carpenter but also the 'processing' of the machine and in conclusion, the final revealed product. We, therefore, have to confess that a carpenter with a machine, is a different carpenter than on without.

## CONCLUSION

This paper has to be seen as a further contribution to the ongoing discussion of human-machine collaboration. The carpenter in this case made use of modern CNC technology and furthermore found a way to reintegrate his singular expertise when constructing with wood. Knowledge that was crucial for the last few hundred years, but then pushed back over the last decade, now reappeared as contemporary interpretation. In this case, another approach of a human-machine collaboration could be observed. Therefore the 'machine' did not only optimize speed and precision of production but furthermore enabled the application of wooden connections that otherwise would not be affordable anymore.

The solution, developed by Berchtold suggests a reintegration of human knowledge into modern production technologies while acting in awareness to his craft specific historic roots.

By developing a solution that follows a line of historic instruments (axe, saw, etc.) but acts with the current state of technology, he could develop an ap-

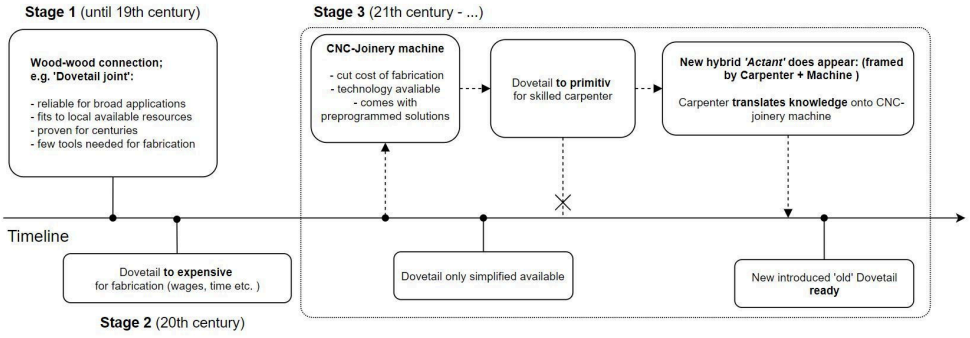


Figure 6
(Re-)Evolution of the Dovetail in this Casestudy; When illustrating this process of 'reintegration of traditional knowledge', three characteristic stages have to be considered: 1) the 'historic craft', when building material was costly and in comparison, wages were low (until 19th century). 2) The 'industrial solution': when wages rose in comparison to material cost and therefor cheaper solutions than the 'wooden dovetail' were available (20th century). 3) The now available technological solution (CNC-joinery-machine) offers the possibility to fabricate historic solutions at a fraction of cost. The provided case study shall illustrate this process of 'reintegration of traditional knowledge'.

proach to meet his definition of modern craft. This moment of translating knowledge between human expertise and upcoming robotic solutions frames the core of this research and therefore will be further explored in the next steps of this ongoing research project.

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# Designing with a Robot

## *Interactive methods for brick wall design using computer vision*

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*The deterministic and linear nature of robotic processes in architectural construction often allows no or very little adjustments during the fabrication process. If any need for modification arise the process is usually interrupted, changes are accommodated, and the process is resumed or restarted. The rigidity in this fabrication process leaves little room for creative intervention and human activities and robotic process are often considered as two segregated processes.The paper will present and discuss the methodological and design challenges of interactive robotic fabrication of brickwork with an industrial robotic arm, a webcam and bricks with varying color tones. Emphasis will be on the integration of external computer vision libraries within Rhino Grasshopper to augment the interactive robotic process. The paper will describe and demonstrate a framework comprising (1) robotic pick and place, material selection and evaluation using computer vision, (2) interactive robotic actuation and (3) the role of human input during a probabilistic fabrication-based design process.*

**Keywords:** *interactive robotic fabrication, human robot collaboration, computer vision, masonry, machine learning*

## INTRODUCTION

Deterministic nature of robotic fabrication processes usually leaves less room for adjustments compared to manual crafting. In the need of any minor changes or adjustments the process is often interrupted and after the accommodation of the changes the process the restarted. This rigidity in the workflow seldom leaves any room for creative adjustments in the fabrication. Design and fabrication often become two different and disjoint processes.

This paper investigates a computer vision-based design and fabrication setup using a collaborative robotic arm. Through visual analysis and machine learning based framework, this paper intends to contribute in human robot collaboration in construction. The work presented in the paper constitutes a set of methods in a sequence to enrich interaction between mason and a robot while advocating "thinking through making"(Ingold, 2013). This work, while performed in a controlled indoor environment, is a foun-

dation for on-site robotic collaboration and exploring material attributes with robots.

Former applications on computer vision and masonry/stacked structure can be categorized into two groups; 2D image based visual analysis and stacking (Dörfler, Rist and Rust, 2013) and 3D point cloud based(Elashry and Glynn, 2014). In the first case, the computer vision was used for picking up objects by extracting position from the image feed. In the second case, computer vision was used to fine tune a robotic brickwork by removing excess mortar while mimicking human behaviour. For human robot interaction, there has been significant number of works in past years but particularly in masonry the AR-VR based collaborative models (Johns, Anderson and Kilian, 2020) have been useful to classify the modes of collaboration. Application and implications of human robot collaboration using a novel framework has been discussed by Dubor et al (Dubor et al., 2016) and Moorman et al (Moorman et al., 2016)emphasizing the importance of sensing and feedback into a deterministic task framework.

Potential solutions for the issue might be relatively new to architecture and construction but has been used extensively in industrial robotics. Computer vision to detect and pick up objects has been commercialized by many companies and marker based detection has also been used extensively as mean of localization in recent times(Handle| Boston Dynamics, 2020)(Pick | Boston Dynamics, 2020). Machine learning and colour detections has also been employed as the part of framework to facilitate interactive robotics. The first part of the project uses visual analysis and colour detection using a curated dataset from bricks of 3 major colour category; the second part uses the data from the previous stage to control the robot and the third part integrates the human input into the robotic workflow breaking the deterministic nature of the workflow.

This paper will present a computational framework ( Fig. 1) for on-site robotic collaboration based on computer vision, machine learning and robotic control. Firstly, it will present computer vision methodologies to determine the pick and place position of the bricks; secondly, a machine learning model will be explained to categorize the colour of the brick. Further, it will present a robotic design method based on the previous methods to imitate human-like aesthetics in a brick wall.

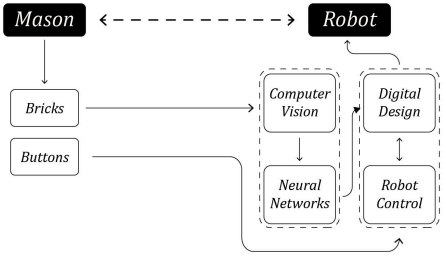


Figure 1
Framework of the system of the experiment

## METHODS & SETUP

The project uses a combination of computer vision, machine learning, robot control and computational design to augment a physical design setup to experiment with the collaborative robotics. (1) Computer vision (CV) and machine learning(ML) is used to delineate the brick in a physical space and identify the colour for the robot control and computational design system to use. (2) The computational design receives the colour data and brick number from the previous step to perform a user defined distribution over the brick wall. (3) Combined with CV and design of the masonry, robot control handles the brick either to the mason or directly in the bond pattern.

To facilitate a collaborative design environment using different coloured bricks as a medium a physical and computational design system was created. This helped the design to be realised by a mason and a robot with assistance of a vision and localization aid.

### *Physical Design System*

The collaborative design environment was developed around a UR10 robot attached with a SMC pneumatic gripper and 2 push buttons. The robot

is placed at 320 mm from a table surface of 2100 x 1220 mm. In order to explicitly define the workspace, the corners of the table has been marked with ArUco marker. These square fiducial markers)(Garrido-Jurado et al., 2014) are used in for precise translation (or transformation) of the physical design space to a digital design space with appropriate scaling reference. This physical setup ( Fig. 2) is aided by an overhead Logitech Brio 4K webcam which conducts the visual analysis of the system. Due to this physical configuration, visual analysis is limited to XY plane of the setup, mostly in two dimensions.

While facing the setup, approximately 700 mm from the left is dedicated for brick placing and pick up and rest of the table space under the boundary has been used for design and collaboration. This approximate dimension help the collaborator to maintain a boundary between design space and material setup. For the construction process bricks of DNF (Danish Standard Bond) format is used having dimension of 228 X 108 X 54 mm. The brick stock has an uneven distribution of red, grey and yellow colour among them. It is necessary to mention that due to a skylight in the test environment the light condition had varied between warm and cool tones based on the season.

### *Computational Design System*

The experiment used a combination of Rhino-Grasshopper and Python environment to describe

Figure 2
Experimental Setup involving, robot, end effector, vision system and working table

the computational design system. This computational system is designed into three subcategories viz. computer vision and visual analysis, geometric computation and robotic manipulation with state machine.

**Computer Vision and Machine Learning.** OpenCV (OpenCV, 2020) with Python binding has been used a computer vision tool for this project due to its wide range of applications, ease of access and large community support. It helps translating the physical design space to a digital twin. It uses ArUco markers to determine the boundary of the work surface and maps the physical existence of the table to a digital instance using perspective and distortion correction. Once it recognizes the white table surface it subtracts the background to analyse the content of the table viz, bricks, brick colour and position. On recognition of brick and its positions, a small machine learning model made using Tensorflow-Keras(Keras | TensorFlow Core, 2020) is invoked to recognize the colour of the brick and classify between, red, grey and yellow category. This part of the design setup is stored as separate python script files and invoked from Grasshopper as a sub-process to run externally to save time and memory. Each of these pieces of code are invoked by a state number and the output is sent using a UDP protocol to a unique port in Grasshopper.

**Geometric Computation and Robot Control.** In the Grasshopper environment, on the design space, a parametric brick wall is generated using native components. The design of the wall has been kept simple as the main goal was to experiment with the distribution of the colour of the bricks using a human like sensibility. Grasshopper allows the user to flow the data from left to right without an option to use the generated data to feed into the previous process. To overcome this issue a state machine(Finite State Machines, 2018) is also developed using grasshopper add-on Metahopper(MetaHoppper, 2020) to control the flow and sequence of the algorithm.The robot control is designed based on Vicente Soler's Robot framework to control the UR10 for pick and place of the bricks. Some part of the code also uses the python package URX (URX, 2020) to move and control the robot for the ease of use in the visual analysis process.The brick designing algorithm identifies the colour of the brick based on the colour of nearest neighbours and colours available in the brick stock ( Fig. 3). The algorithm uses a heuristic solution for the colour solution rather than a stochastic solution, keeping in memory the available colours at a particular time. This implies that the solution might not be the most optimum one but the best one, given the availability of the bricks.

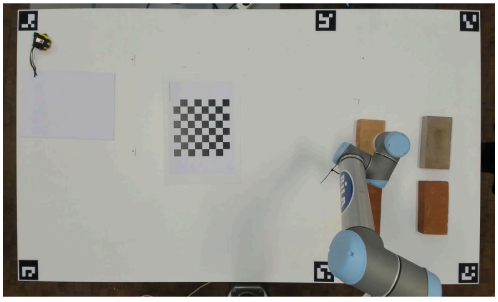

Figure 3
Robotic workplace setup and calibration. View from top mount camera

Development of a collaborative system implies a certain amount of sensing from the machine part to collaborate with a human. Implementing this process through 2D image-based computer vision was a relatively easy task compared to other sensing methods including 3D scanning of point cloud generation. These methods are much more resource intensive and in most of the cases require a special API or SDK to compute. Image based CV helps establishing the sensing using less resources and in less time. Due to the lighting situation in the test environment, the perceived colour of the brick differs in time in various seasons. This implies that it is not possible to identify the colours of the brick using an absolute model. Implementation of a simple machine learning model helped overcoming this issue. For the experiment, four varying shades of yellow brick, fifteen varying shades of grey bricks and 13 varying shades of red/orange bricks were procured from the material library to create a colour recognition dataset. These

were photographed using the same webcam in various light condition. The labelled colour data is fed into a simple supervised prediction model. Using this model, the colour of the bricks is determined after the background subtraction. This increases the accuracy and the detection and works in light conditions varying from warm to cool.

The goal of this experiment is to collaborate with a robot to imitate human sensibility in a particular task. Due to this reason the design of the wall has been kept simple but not generic to explore the possibilities of robotic collaboration through actuation. The majority of the setup is based on an interaction basis where the user interacts with the system using two push buttons to assert the next step of the process. To create such behaviour within Grasshopper, state machine setup is used where each state is invoked on fulfilling a certain condition, completes a particular task and triggers another state based on either the output of that particular state or by human override. This helps to control the interaction process from one single environment. These state numbers are also the same input that externally triggers the python files in order to complete tasks based on visual communication.

The design of the masonry is developed incrementally based on the number of bricks on the table and their colours. The algorithm uses a simple neighbouring rule set to create a colour distribution and variation. But it also improvises the assignment of the colour based on the colour of the brick available. This can be overridden by the collaborator and the input will be passed to the designed algorithm to predict on the colour. This gives an equal leverage to the human creativity also to a designed algorithmic intelligence of the system.

The robot acts as an active collaborator and mostly acts as a helping "arm" to collaborate with human. The algorithm beneath the robotic manipulation and pattern generation in real time provides the placement planes and robot actuation is occurred through those planes.

## DESIGN EXPERIMENTATION

Robotic masonry has been under development since the last decade but in majority of the processes are either fully automated or leaves a very little room for human intervention; mostly at an operator level(Piškorec et al., 2019). The only intelligence used in the design process is the algorithmic intelligence. Specifically, in this project, it has been studied how the human creative agency can be augmented with the algorithmic intelligence and computational design exploration (Fig. 4).

Figure 4
Example of colour variation in a masonry work. Photo by authors.

The collaboration process does not start until certain predefined number of bricks of varying colour is placed by the human ( Fig. 5). These colour of the bricks acts as the design driver (seed of the pattern) the further set of bricks based on the colour of the brick available on the table. This step is used as an augmentation to the creative agency by the human and reciprocation the behaviour is observed in the due process.The experiment is designed to generate a simple non-repeating pattern based on the colour variation of the bricks. To achieve this goal, the human and the robot works together and both the agencies' decision are influenced by each other. During the experiment the following points have been studied:

- The material setup is done by the human collaborator. Hence, the probability of the randomness in the colour distribution of the bricks could

vary at each step. The algorithms ability to generate the randomness of the pattern was the first thing that was studied. Masons, through their experience, can vary the colour of the bricks in a bond to avoid repetition. It was observed how the system behaves through this change.

- Following system generated results, it was observed how the mason behaved to the designed pattern. It was also observed how much of the algorithmic pattern was accepted and retained by the mason and what kind of influence it left on the creative persona of the mason.
- Finally, it was also studied by varying the robot speed at what speed and acceleration the mason was most comfortable to collaborate with the robot.

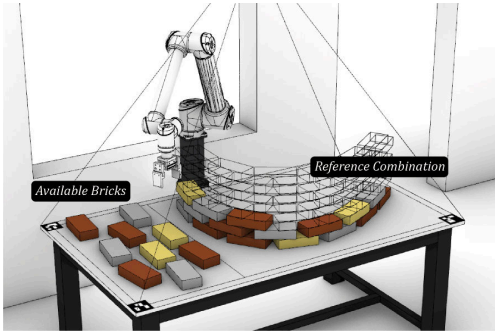


Figure 5
Experimental setup after laying initial bricks and available bricks on table

## RESULTS

The result of the experiment yielded in insights into the process. These results can be categorised into two categories; (1) results owing to algorithmic intelligence, (2) results due to robotic actuation.

### *Algorithmic Intelligence*

Two neural network models have been utilized to automate and suggest the task. First one was to determine the colour and second one was used to predict the possible colour of the brick for a combination. First one, reduced the time of a process of identifying the colour in contrary to a computing the position of the colour on based on Euclidean distance in a LAB colour space. The second neural network predicted the best possible colour combination based on a model which also reduces the time to compute the combination compared to a search algorithm. Particularly this has resulted into a lower waiting time for the collaborator to keep the creative flow almost intact.

### *Robotic Actuation*

The robot has been used as an agent to aid the human in the construction process. The accuracy of the robot has been used to realize the non-standard placement of the bricks in the masonry. The freedrive mode of the UR10 also has been utilized to digitize a brick in case of manual override of the brick placement and to update the brick in the digital twin.During the conduction of the experiment the system used an IDE( Fig. 6) and Grasshopper ( Fig. 7) as its main user interface.

Figure 6
Background subtraction and prediction from one of the neural network

The vision system and the prediction system used the IDE and Grasshopper was used for the design and robot control. This lacked a unifying user interface to for the collaborator to concentrate on. The decision of the robot was not available to the mason till the point of robotic actuation. This possibly created a sense of disconnect with the robotic system and the physical design system.

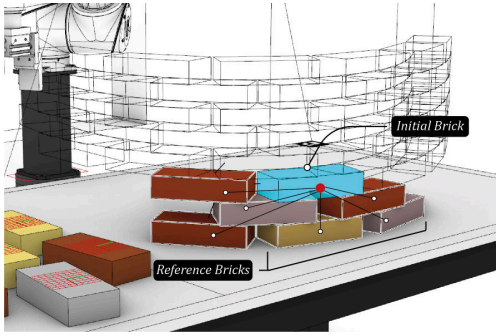


Figure 7
Colour of the brick to be placed(in blue) is to be decided by its 6 nearest neighbouring bricks and available brick on the table.

## DISCUSSION

Following this study of human robot collaboration through a vision system, some important aspects of design collaboration and technical improvement has been revealed.

This experiment is a model of an on-site construction collaboration. This has been conducted in a controlled lab environment which is usually different than a construction site. The identification of the brick and the pickup zone is hard coded into the system using markers and easy detectable white background. In the construction site, it could be still marked by a marker but the brick detection can be done using a semantic segmentation. This is helping the model to the utilized in a various construction scenario.

The pattern prediction model has been trained on a supervised data set for the time being with 2430 possible combinations generated by another algorithm and curated by a designer. This will reflect a designer's bias on the pattern generation. The possible solution to overcome or augment that bias is to implement a recurrent neural network (RNN) to predict the pattern using the semantics of the masonry pattern. Collaboration between human and robotic arm with aid of neural networks has considered two agencies working together in order to achieve a design goal. In this scenario the robotic arm, augmented with a computer vision system, contributes to the brick handling and pattern suggestion process. The machine learning model used in the process, can be biased with the data available at a point of time based on the availability of the bricks. The decisive and exhaustive nature of the creative tasks, leaves the process with many variables. This presence of many variables contributes to the higher computation time to interrupt the design flow. In a collaborative process of this nature, it will be efficient for human to handle the decisive and exhaustive creative nature of the process while robot handles the more precise and analytical aspect of the task.

The present goal in this demonstrator was to create a random pattern using the available bricks. But it is possible to replace the evaluation criteria of the placement of bricks with thermal or acoustic performance of the wall where the creative agency of the human can be collaborated with the analytical and computational model of the machinic system.

The experiment has attempted to carry out a foundational task on which several on site application and creative collaboration can be based. It will be important to investigate the common ground of the designer delivering a creative solution, algorithms and autonomous systems generating a performative solution and role of robotics- augmenting the human co-creator by additional dexterity and degrees of freedom.

## ACKNOWLEDGEMENTS

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# Silica

## *A circular material paradigm by 3D printing recycled glass*

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*Silica examines the making of 3D printed tiles from recycled container glass. This paper describes an interdisciplinary exploration into how robot-controlled extrusion can offer new material practices by which to fabricate glass elements of an architectural scale. We pursue working with recycled container glass powder - a waste product derived from the reprocessing of recycled container glass - to contribute to circular development within an interdisciplinary artistic development context in the meeting between architecture and glass design. The project has two aims. On the one hand, it builds an in-depth understanding of the parameters of fabrication and devising means by which to control these through digital design methods and their interfacing with robotic fabrication processes. On the other hand, it critically questions the architectural, aesthetic and performative properties of these material practices and their embedded methods.*

**Keywords:** *Robotic fabrication, Digital design systems, Circular economy, 3D Glass printing, New material practices*

## INTRODUCTION

Silica examines the making of 3D printed tiles from recycled container glass (Fig. 1). By developing methods for robot controlled extrusion of glass paste and its firing (Fig. 2), we develop new practices by which to fabricate glass elements of an architectural scale. The project examines the recycling of container glass powder - a waste product derived from the reprocessing of recycled container glass - and contributes to the construction of circular design principles. The project is undertaken as an interdisciplinary collaboration between architecture and glass design and merges scientific and artistic methodologies. Silica is a collaboration between members of CITA and glass artist Maria Sparre-Petersen.

## CONCEPTUAL FRAMEWORK: GLASS AS AN ARCHITECTURAL MATERIAL

Glass is one of the heroic modernist materials. In his text "Glass: The Fundamental Material of Modern Architecture" written in 1935, Le Corbusier calls for a second machine age in which technologies of manufacture would restore mankind's harmonious relationship with nature. In this lineage, glass as a transparent and essentially non-present material allowed a new conception of architecture as intimately con-

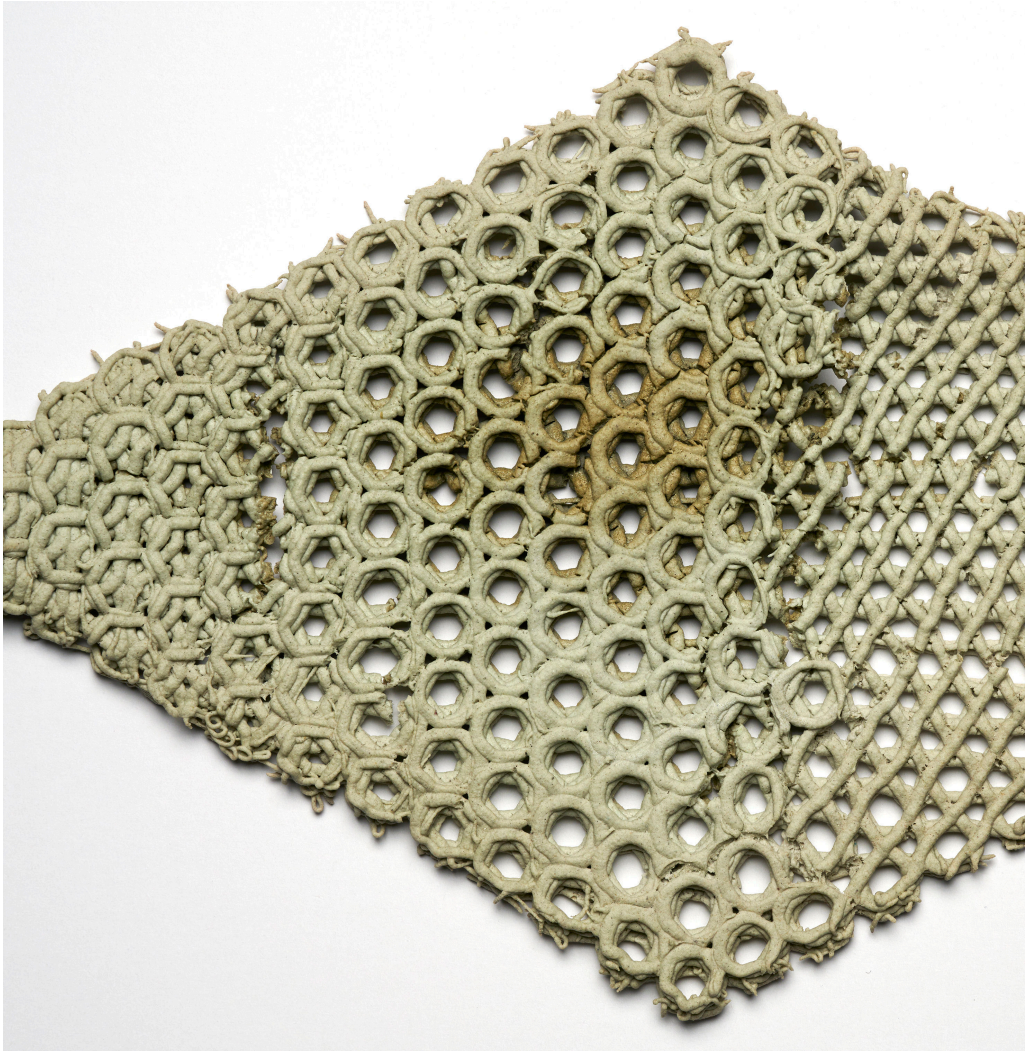


Figure 1
Silica: 3D printing recycled soda glass

nected to its surrounding environment. Maison de Verre acts very differently. Conceived and built by Pierre Chareau in the years 1929 - 31, Maison de Verre is a cornerstone in modernist history. While celebrated for its use of prefabricated glass block walling, it presents the curtain wall not as an open surface, but rather through a translucency dramatically changing as interiors are lit at dusk. Silica takes point of departure in this parallel material opportunity. By examining the 3D printing of recycled soda glass, we explore the making of translucent and opaque glass tiles for architectural application.

In Silica, the ambition is two fold. Firstly, it develops a new material practice in which recycled soda glass powder is mixed with a natural binder in order to create a thick extrudable paste. Secondly, it develops robotic controlled additive extrusion methods by which to form the paste. By building on a paté de verre process, we employ a mould-less fusing process to form and then sinther the glass. The project uses the architectural tiles as a particular site of investigation. Here, we leverage two key properties of the process; the ability to print very fine layers thereby enabling a filigree porous structure and at the same time make the most of a chiefly two dimensional extrusion process. The choice of the tile as an architectural element allows us to contextualise the material investigation within an architectural scenario that leverages new architectural expressions. When printed thinly the material is translucent. The central reason for this is the material resource of recycled soda lime glass powder.

## RECYCLING - GLASS IN A NEW CONTEXT OF PRODUCTION

Silica is understood as a first probe into rethinking how we address recycling in architecture. The vision and ambition of the large framing project is to develop the conceptual, design-based and fabrication-based methods for printing architectural structures locally with recycled materials from demolished buildings. As such, the project ties into wider efforts to redress contemporary industrialised processes and invent the sustainable practices that can rethink how materials are sourced, how they are used and how they are recycled.

Figure 2
3D printing process followed by firing

Concepts of Circular Economy, Cradle to Cradle Design or Integrated Design, as reflected in the UN Sustainable Development Goals, aim at defining design paradigms that challenge the "take, make and dispose" approach of the conventional linear economy, and instead increase awareness of resource circularity, sustainable production and the reconciliation of economic, environmental and social goals (Valero & Valero 2010). Glass recycling in artistic applications has previously been explored by Oseng (Oseng et al. 2009) and Siikamakki (Siikamäki 2006), both through traditional fabrication processes, while the new technological developments afford a wider range of aesthetic opportunity. This idea of reconciliation echoes Le Corbusier's call for restoration of a harmonious relationship between mankind and nature. As we stand before the fourth machine age - industry 4.0 - we find ourselves repeating an appeal for using technology to re-find an environmental alignment, but with a new agenda and a new sense of urgency. The robotic manufacturing offers opportunities for three dimensional printing that are impossible using traditional glass casting techniques, hence, potentially afford new aesthetics as well as structural functionality when we begin to build tacit as well as technical knowledge of how the material can be adapted to the technology. In this first venture into the research we have been able to accomplish the first step of adjusting material to fit the equipment, laying a foundation for exploration of more complex three dimensional structures.

## MATERIAL

Glass is 100% and infinitely recyclable without loss of material qualities (Fig. 3). As such it presents an interesting case for circular resource thinking as opposed to materials like ceramics and concrete that can not resume earlier material states after being transformed through firing and curing.

Figure 3
Soda lime glass is a highly recycled material. In Europe 74 % is recycled. Sweden, Belgium and Slovenia recycle more than 95 %. On the global scale recycling amounts to 35%. For every six tons of recycled glass used as an alternative to virgin materials in production processes, carbon dioxide emissions are reduced by one ton. Over a ton of raw materials are saved for every ton of glass recycled. Besides reducing emissions and consumption of raw materials, recycling extends the life of plant equipment, such as furnaces and saves energy as energy consumption drop about 2-3% for every 10% cullet used in the manufacturing process [1].

Globally, the call for new sustainable material practices for glass production is urgent. Glass is made of sand and sand is a finite resource. Due to the exponential increase in the use of concrete and flat glass in the building industry we are running out of buildable sand resources (Bendixen et al. 2019). Currently, waste glass from the demolition of buildings has not so far found any use in the production of new flat glass (2). As requirements in terms of purity of raw materials for the production of flat glass are extremely high, waste glass from buildings becomes in most cases landfill (3). Silica presents ways to recycle glass waste in an architectural context. For our experiments we work with recycled container glass, which has the same molecular structure as flat glass, it is already being recycled at an exemplary rate in a functional circular system in most European countries, it is abundant, cheap and readily available in most parts of the world, hence the project is potentially applicable on a global scale, which is important with regard to impact.

This material choice also makes the project very different to other efforts in 3D printing glass. In recent years, attempts at printing glass have been successfully completed by Markus Kaiser (4), in his artistic project Solar, where he built a 3D printing rig, powered by the sun, that sintered glass directly on site in the desert. MIT media lab has developed a melting kiln that extrudes clear glass similar to a regular 3D printing process (Klein et al. 2015). RISD has created a system with a platform that moves underneath a vessel with a hole, filled with hot glass that runs through the hole and forms a somewhat chaotic geometry (5) and KIT is printing the glass through a complex process combining nano technology, polymer support structures, light- and heat sintering (6).

In difference to these processes Silica develops a two-part process in which the 3D extrusion of the glass paste takes place before the firing, exploring mainstream equipment that allows knowledge sharing with a broader research community. Furthermore, the crystal class explored at MIT, RISD and RIT offers clarity and transparency, while the architectural opportunities are limited because of the chemical composition of crystal glass that is more brittle, has less impact strength, cannot be recycled in the regular recycling stream and is more sensitive to temperature than the recycled sodalime glass from containers and windows, used in this research. Aesthetically, the opportunities of the sodalime glass combined with the fusing technique are quite different from those of the crystal glass. When printed in a thin layer the material is translucent while when the material is printed in several layers the sintered glass becomes opaque due to the devitrification of the glass. This allows us to control the translucency through layering. Furthermore, the extrusion process allows small scale control of deposition and therefore a highly detailed forming of each deposited layer allowing us to control the structure of the print and introduce interstices between print lines. By introducing dyes to the material paste we can also grade colour across the extrusion process. In Silica, these processes are combined to form complex elements that change in translucency, colour and structure expanding the understanding of how glass is used and how these new meanings may influence future circular visions within architecture.

## TECHNIQUE

The innovation in Silica is both its circular material logic as well as its forming process. Through experimentation we have developed and understood how these parameters change as the material composition varies and how the robotic fabrication process can be steered through design algorithms.

A core innovation is the developed sustainable structural additive, which the glass powder needs to work with the printing process. Tests with water and glue proved unsuccessful, hence, we settled with a flour/water/glass mixture that mimics clay which works well with the robotic digital design process. As opposed to clay that shrinks as a solid body during the firing process the flour in this mixture burns away and leaves a porous structure. When the material is too thin this causes disintegration of the tiles (Fig. 4).

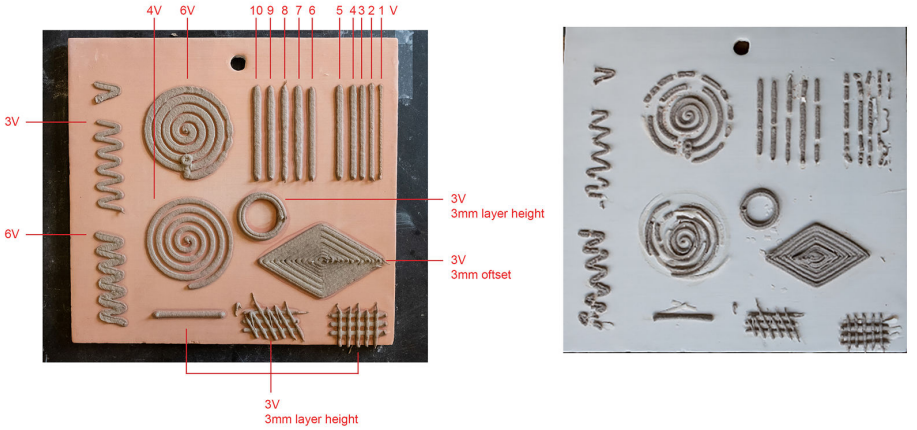



Figure 4
Topology tests of print and firing parameters. Several parameters, such as duration and max temperatures of the kiln program, layer thickness, connectivity, distance between nodes determine, whether the prints shatter during firing or not.

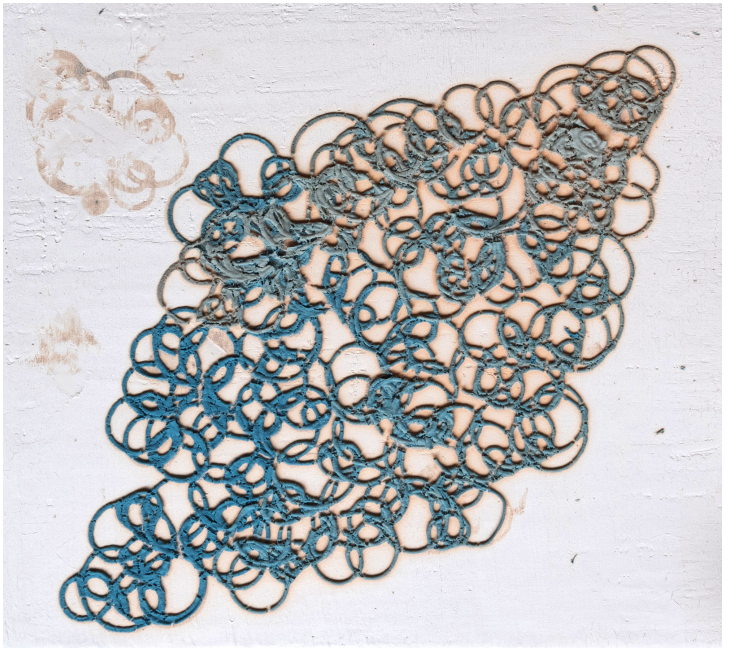


Figure 5
Adding graded colour to the glass paste

To avoid this, experiments conducted with different geometrical layouts during the 3D printing, as well as with more layers in each print led to the conclusion that several layers of mixture has better structural coherence, though too many layers make the structure warp and collapse. Using the fusing process with the equipment available at the KADK, we have achieved successful results with this material at a small scale. A real life situation would require rigorous systematic development of technique and material in order to secure reliable results in a large-scale production. While this is not the scope of the project we do suggest it may be a viable route for future architectural projects.

An opportunity in this process of making is the adding of colours. For this purpose, we have used ceramic stains that fire up to 1300 degrees Celsius. By varying the amount of stains added to the material mixture, which regulates the saturation of the colours. Furthermore, we have investigated ways of creating continuous colour gradients by filling varying colours in the same printer cartridge (Fig. 5).

The paste is 3D printed through an extrusion process. For this process, we have developed bespoke tools for extrusion that allow us control over the flow rate (Fig. 6). The set-up consists of a robotic arm with an attached tube that feeds the glass paste from the printer cartridge. A linear actuator ram feeds the paste to a ViscoTec dispensing pen attached to the end of the robotic arm that allows us to stop and start the printing procedure according to the design and gives us control of fine printing. Glass has an inherent capacity to become 6 mm thick upon fusion, which coincides with the fact that the mixture needs a high concentration of flour in order to flow properly through the dispensing device and avoid pulling apart in the firing. The print paths are therefore scaled to these inherent material properties.

Once the print is completed, the material is fired in a ceramic kiln. Through experimentation we have found that the best temperature for sintering is 950 o C. Where higher degrees improve sintering, the material sticks to the separator and the layout of the pattern is blurred. Due to devitrification, a termochemical process that transforms the glass from an amorphous to a crystalline molecular structure, the fired material is no longer classified as glass. Nevertheless, if the material is recycled it will still be compatible with soda lime glass and be able to turn back into the amorphous glass state if fired at higher temperatures. During the firing process, the material contracts which may cause points of cracking if the material cannot contract uniformly. To prevent this breakage, we have developed methods of using the design of the patterns to strategically deposit the material for controlling the contraction (Fig. 7).

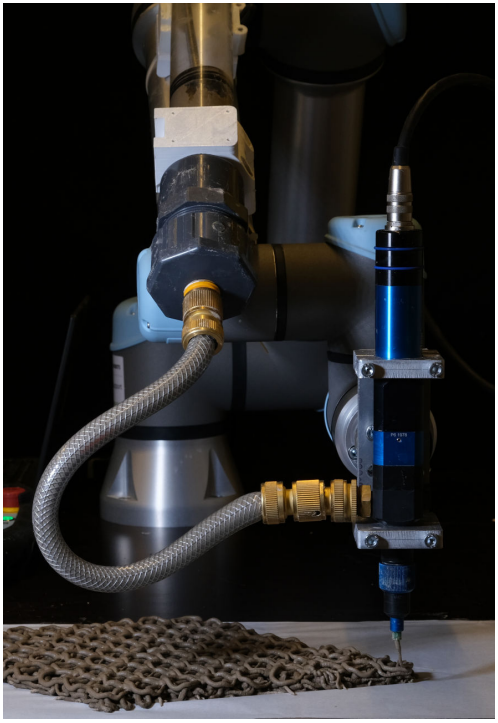


Figure 6
Final printing setup printing tool using a self developed cartridge system for glass paste and a professional volumetric dispensing system.

Figure 7
Contraction in the firing process

## DESIGNING THE SILICA PATTERNS

In order to control the thermo-chemical material behaviour, we have chosen to work with long continuous line patterns to generate the toolpaths for the tiles. The needed consistency of the paste for the kiln firing procedure lowers the general precision during the printing process. Working with continuous lines requires less stopping and starting of the extrusion process and a higher degree of precision. Through experimentation, we have learned that working with directionality, continuity, density and overlapping allows us better control of the deformation during the kiln firing process. Inspired by spirograph drawing in which seemingly complex continuous lines are controlled through simple mechanisms, we have developed a system for creating continuous patterns, which can be steered by adjusting the amount of self-intersection points in defined areas to vary the density and thickness of the tiles. The entanglement of the lines create adhesion between the layers, which bond through pressure of gravity in the kiln. Working with longer continuous lines also gives the opportunity to load varying colours into the printer cartridge to produce seamless colour gradients throughout the tiles.

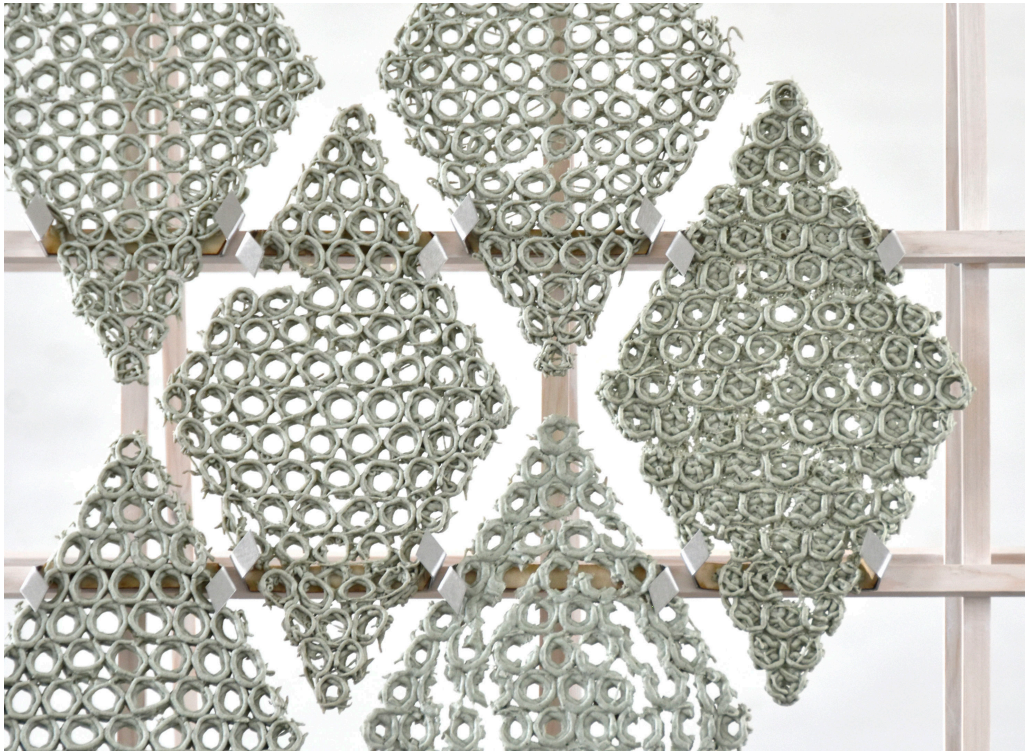
To test the material in an architectural scenario we have developed a shingle system by which the tiles are assembled into an architectural skin. The tiles are graded in their pattern, controlling the porosity in respect to light penetration. Bespoke brackets attached to an underlying scaffold are carrying the tiles in custom angles to avoid joining of fragile tile boundaries and to alter the experience of the screen from different viewpoints (Fig. 8). The prototype system consists of 11 individual tiles, varying from dense to sparse patterning, creating an overall screen.

## CONCLUSION

Silica examines the 3D printing of glass materials through a two fold process. It develops a new material practice by mixing a new glass composite and creates novel forming processes. It builds an in-depth understanding of the parameters of fabrication and devising means by which to control these through digital design methods and their interfacing with robotic fabrication processes. At the same time, the project critically questions the architectural, aesthetic and performative properties of these material practices . By using the architectural typology of the tile as a place of investigation, we ask how these new material practices can suggest new ways of understanding architectural boundaries through conditions of porosity, translucency, colour and pattern. Combining two conditions, one creative, circular and technological, the other analytic, conceptual and designerly, we are interested in understanding how these new circular material practices extend existing architectural vocabularies in aesthetic, conceptual and practical ways.

Further research perspectives lie with further developing the composition, forming process and firing of soda-glass based pastes. Where robotically steered processes can allow for the forming of more 3-dimensional pieces it will be important to understand how these pair with adequate firing processes. At this stage our interest has been to understand the material in the context of architectural applications, then future research will examine applications across product design, industrial design and further architectural scenarios in which the open structures and inherent porosity can find further application.

Figure 8
Silica: assembling graded tiles. Tiles attached to scaffold with aluminum brackets




## ACKNOWLEDGEMENTS

The project is undertaken as an interdisciplinary collaboration between architecture and glass design and merges scientific and artistic methodologies. Silica is a collaboration between architects Mette Ramsgaard Thomsen, Martin Tamke and glass artist Maria Sparre-Petersen with research assistant Emil Fabritius Buchwald and architecture student Simona Hnídková.The team thanks Reiling A/S, who has provided 1 ton of waste soda lime powder as a donation to the project. Reilling is the sole processor of recycled glass in Denmark, supplying cullet for the container glass production company Ardagh Holmegaard A/S.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# SoRo Responsive Wall

## *Soft robotics for human-oriented architecture*

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*Designing and making an interactive architecture that is able to respond to the environment and human behavior generally requires a variety of mechanical and electronic devices, different kinds of joints and components, and sometimes dangerous equipment that may harm users. They mostly consist of rigid materials which usually need to be covered or modified to be more appealing and pleasant. What if the structure itself feels comfortable and friendly, and moves gently in order to create a bonding with people? In this research, we propose a soft architecture that can interact and respond using soft robotics principles. We have designed a human-friendly soft robotic wall, that can function as a shelter in urban spaces and changes its form by human presence. Utilizing pneumatic actuation along with soft materials using simple mechanisms results in a safe and soft architecture. Through several prototypes within which the movement of the module is studied and analyzed, we used cloth and air balloons instead of silicon in the 1:15 model to create an inexpensive module that is feasible on a 1:1 scale.*

**Keywords:** *Soft Robotics, Responsive Architecture, Interactive Architecture, Human-Oriented, Soft Architecture*

## INTRODUCTION

With the intensified social and urban change today, the demand for Interactive and responsive architecture solutions has increased. Rooted in the 1940s, by the emergence of cybernetics, architects showed interest to employ its concepts in architecture to envision open-ended user-driven environments (Yiannoudes, 2016). In the late 1960s and early 1970s, the first concepts of responsive architecture were introduced by Pask, Price, Negroponte, and Eastman (Negroponte, 1976). It was evolved through the years and now architecture has the ability to learn, respond, interact, and predict (Kolarevic, 2009). While nowadays most of the interactive and responsive solutions in architecture are related to maximizing human physical comfort and minimizing environmental impacts, human's mental comfort and satisfaction in relation to the architecture is lost in the technological advancements and innovations. As one of the groups concerning the relationship between architecture and human emotions, we can mention the Hyperbody Research Group (HRG) where the so-

called "E-Motive Architecture" concept was developed by Kas Oosterhuis (Oosterhuis, 2003). We believe that using soft robotics in parallel with adding a layer of intelligence to pneumatic structures can lay the foundation for designing the future of "Soft Architecture" (Broady, 1967).

Our main objective in this project is to take both aspects of responsive architecture into account. We propose creating an interactive structure for use in public urban spaces or exhibition spaces to act as a gathering point and shelter for pedestrians and visitors. Simultaneously, this structure has to respond to human presence in such a way that the users feel comfortable and secure.

## METHODOLOGY

This study has adopted a hybrid approach of theoretical studies, comparative analysis of case studies, material analysis, and physical prototyping. Firstly, after determining the design problem, we have studied the field of soft robotics and its potentials to be used in responsive architecture. Secondly, the scarce literature of soft robotics application in architecture and case studies was analyzed regarding their design, material and actuation method. Thirdly, the design was evolved through prototyping and testing various materials and methods. Finally, a model representing the core idea of our design was built on a 1:15 scale in High-Performance Architecture Lab (HAL) at TMU, Tehran. We have used Rhinoceros software and Grasshopper plug-in for modeling and simulations, Arduino kit for processing and Arduino IDE with C++ language for programming.

## SOFT ROBOTICS

Generally, there are two methods in robotics that can be used for making movement in a machine or structure: Soft and Rigid. Rigid robots mostly consist of a complex combination of solid parts, gears, cylinders and etc. which results in high accuracy and power. They are highly specialized but don't have the ability to adapt the environment. So they rarely exhibit the rich multi-functionality of natural organisms. They can be highly dangerous and have the potential to cause injury to humans. In contrast, Soft robots are primarily composed of easily deformable matters like gels, elastomers, fluids. Representing elastic and rheological properties of soft biological matter found in nature, they can adapt their shape for a broad range of environmental conditions and tasks without damaging themselves and humans (Majidi, 2014). Moreover, they usually use simple mechanisms, therefore they are not expensive. To conclude, hard and soft mechanisms are complementary. Hard robots can be used where power, precision, and speed are a priority and soft robots can be employed where

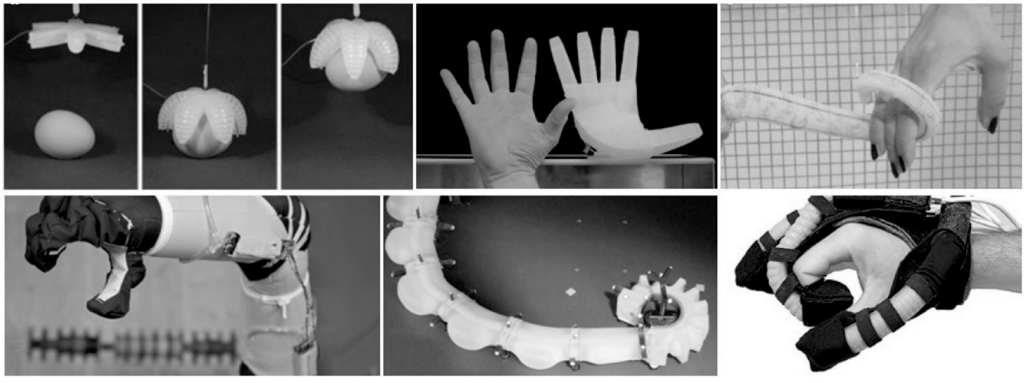


Figure 1
Examples of soft robotics manipulation systems. (Source: Rus and Tolley,2015))

flexibility, safety, and simplicity are in favor. During the last decade, the amount of research in soft robotics has skyrocketed and has brought substantial achievements in terms of principles, models, technologies, techniques, and prototypes (Laschi, Mazzolai, & Cianchetti, 2016). (Figure 1)

After reviewing both rigid and soft robots, and studying their applications in architecture, we have summed up that soft robotics methods are more suitable for our purpose. Because they can provide the opportunity to fill the gap between machines and people, they are more adaptable and less dangerous to humans, and they have the ability to perform complex movements to create various forms.

## PRECEDENTS

Although the design and actuation of soft robotic systems are rooted in the 1990s (Rus & Tolley, 2015), first attempts to apply them in architecture dates back to 2014, where a workshop was held in the department of architecture at ETH, Zurich, introducing soft robotics to architecture students. They have proposed a building façade concept that integrates soft robotics (Dino Rossi, 2014) (Figure 2c). Subsequently, other researchers have developed this field. Similar to the workshop, most of the research was focused on creating or controlling panels that can be used on building façade [1]. In these projects, generally, a soft robotic actuator is used to change the direction of a panel. This results in controlling the amount of interior light or tracking the sun position by a solar panel. We can also mention a group in Material Dynamics Lab at NJIT, US, focusing on using soft robotic silicon actuators as a thermal and acoustic insulator as well as a visual barrier (Decker, 2015) (Figure 2b). According to human interaction, we can also mention the following projects: First, In Interactive Architecture Lab at UCL, England, a group of students has created a face mask named Aposema serving as a soft robotic interface for augmented reality [2]. Second, MIT Media Lab has developed Aeromorph, heat-sealing inflatable shape-change materials for interaction design (Ou et al., 2016). Third, A Modular PneuNet based system is developed by Kim et al. which can be duplicated to form a responsive wall or even used as wearables(Simon Kim, 2015) (Figure 2a).

In all the above mentioned except the Aeromorph project, silicon elastomers were used to create actuators. Regarding the case studies' building method, in addition to modularity, two major approaches can be perceived: First, the actuators itself shapes the body structure and creates the architecture. In this method, the softness of the body is demonstrated but the scalability of the prototypes is a challenge because the silicon material is expensive and molding and casting silicon in large architectural scales is not feasible. Second, the actua-

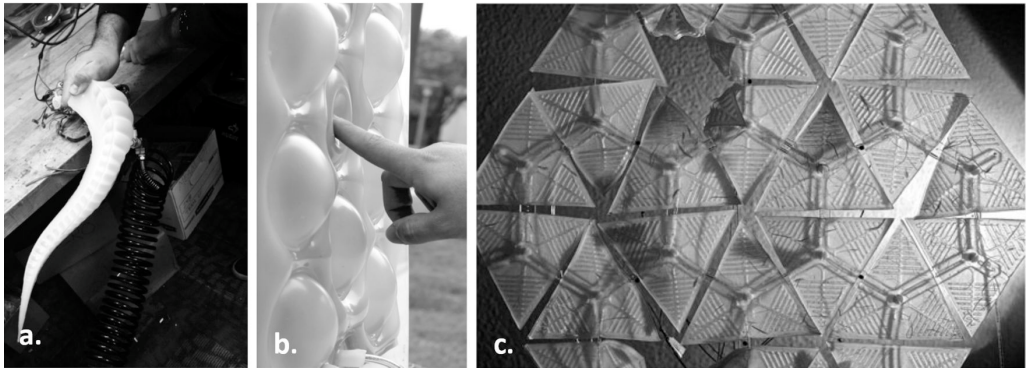



Figure 2
a. Pneu-Net module (Kim et al., 2015) b. Soft Barrier (Decker,2015) c. Responsive façade (Rossi et al.,2014)

tors are used to move or rotate another structure. Here, the mechanical properties of the soft robots to perform complicated movements were employed, rather than representing the feeling of softness. In our project, we took first approach into account, and we tried to translate the Pnue-net silicon actuators to another feasible and scalable method.

## DESIGN

Our main concept in this project is to create a satisfying and comfortable place in urban spaces for people to feel protected and beloved. The idea is a simple wall (barrier or shelter) that reacts gently to both human presence and the environment. We improve the quality of space in two aspects:

- Environmental conditions: By bending, the structure can be a shelter for people in times of heavy rain or sun. In hot summer or cold winter, it can modify the inflated air temperature to provide thermal comfort in the surroundings. Also, with various lighting strategies (like lighting inside the columns) it still lives and attracts people at night.
- Interacting with people: This structure can be perceived as a living being that breathes. The inhale and exhale of the air inside the balloons, the flexibility of the structure and the softness of the material enable it to create this feeling. People can lay relax on it like a sofa, touch and feel it, and gather and socialize under its shelter.

The whole structure is consolidated by air pressure. Inspired from soft robotic actuators, we proposed a system consisted of modular air columns that can bend independently at the desired angle. To adapt to different sites, the modular columns can change their organization and number of units to either shape of a path or even a circular shape to make a dome.(Figure 3)

## MATERIAL & MECHANISM

Soft actuators are frequently arranged in a biologically inspired agonist-antagonist arrangement to allow bidirectional actuation. To achieve this, two major methods are used: variable length tendons and pneumatic actuation (Rus & Tolley, 2015). Pneumatic actuation is the most common method which is been used in soft robots. In our opinion, this approach is where the soft robotics and pneumatic architecture meet. It is usually applied with silicon elastomers which are the best materials suited for small scales but not for huge architectural scales. These actuators consist of inner air channels and a strain limited layer on one side (Figure 4). When the air channels are filled with a fluid, it starts expansion. Thanks to silicon flexibility, it can expand on one side but not on the other side. This relatively simple mechanism causes the actuator to bend.

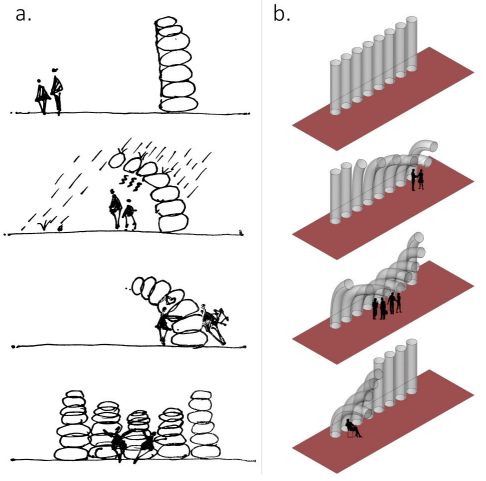



Figure 3
a.Concepts and initial ideas. b. Different possible postures of the structure.

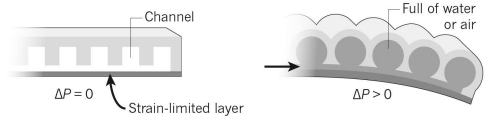



Figure 4
Pneu-Net actuators mechanism.
(source: (Rus and Tolley, 2015))

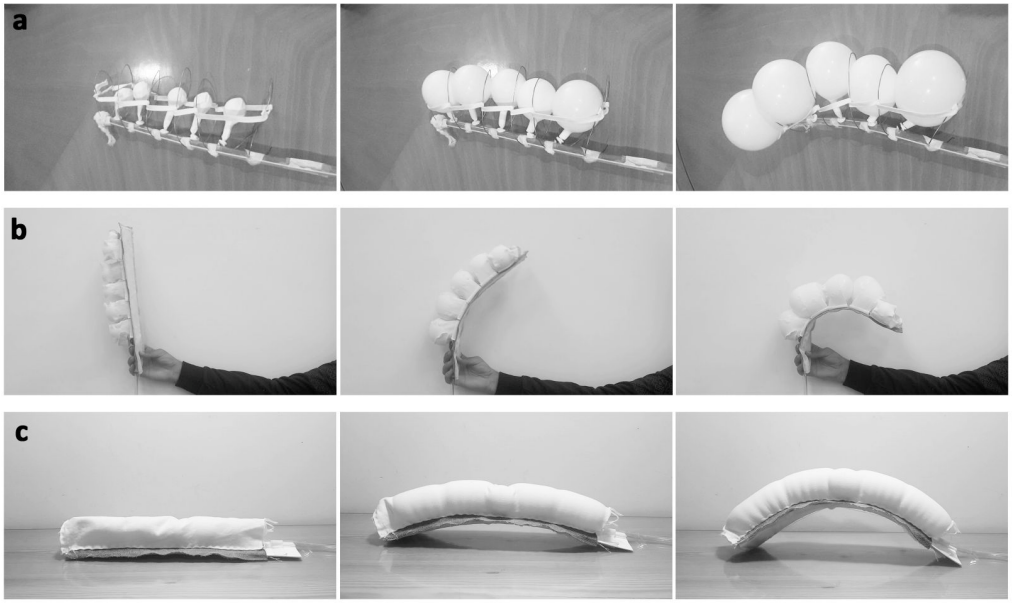



Figure 5
Three prototypes were tested to find the best design solution. Each balloon represents an air channel in the Pneu-Net system. a. The balloons weren't restrained so they can't transfer the air pressure force in one direction. b. Inextensible fabric is used to restrain balloons in position. c. a piece of one-way stretch fabric is used to restrain balloons and direct the air pressure force in the correct orientation.

If we are intended to use low-cost materials, we have to extract the principal parts of the actuation mechanism and create it with inexpensive materials. (Table 1) In this project, we have proposed stretch fabrics for the body of the structure. It is where people start to interact with the architecture and it has to be soft and flexible to feel friendly and comfortable. The fabric has to stretch only in the direction which we want the column to bend. This way we focus the force in the desired orientation. We use air proof nylon or elastic balloons to provide the tension force for bending each column. And finally, any bendable and not extendable material can be sewed on one side to the stretch fabric. In our model, we have used 0.5mm Plexiglas as inextensible material (Table 1). With this idea in our mind, the design was evolved through creating and testing porotypes (Figure 5).

Table 1
Comparison between elements in a Pneu-Net actuator and Columns actuation in the project.

| Num. | Element in Soft robotic Pneu-Net actuators | Equivalent in the project |
|---|---|---|
| 1 | Extensible outer layer (in one side) | One way stretch fabric |
| 2 | Inner air channels | Balloon or airtight Nylon |
| 3 | Inextensible outer layer (in the opposite side) | Plexiglas 0.5mm |

## CONTROLLING SYSTEM

This structure measures environmental factors, such as human presence and weather conditions, to adapt itself and create a better space for users. The controlling system in this project plays an important role and has to be designed as well as the other architectural aspects (Figure 6). It consists of three main stages as is depicted in the diagram. IR, photocells, and temperature sensors are means of gathering environmental data for further process. The data is then processed with an Arduino UNO(Arduino) kit and finally reacts properly by activating output sources. Each sensor respond is as follows: (Figure 7)

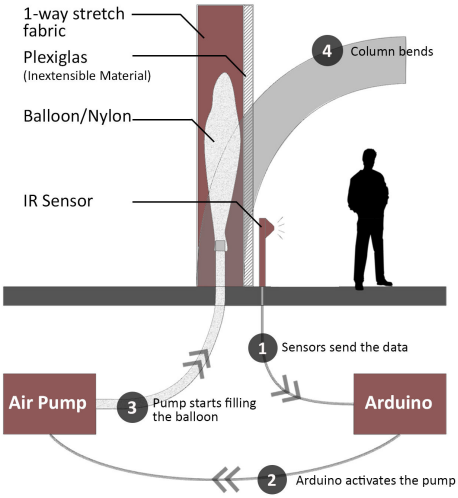



Figure 6
The bending mechanism.

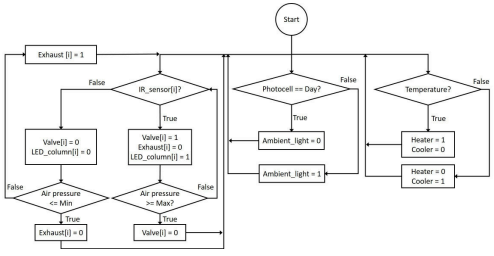



Figure 7
Flow chart of the interactive process.

- IR sensor: If a human is sensed in front of the sensor, the air pump goes on and fills the balloons in the actuators. This will make them to bend. Otherwise, the Arduino turns the pump off and evacuates the air inside the balloons by turning on a servo motor acting as an exhaust valve. A computable amount of air pressure has to be always inside the column to consolidate the structure.
- Photocell (photo resistor): senses the amount of light. The LED lights inside each column can be turned on and off in respond to environment light (day/night) or human presence.
- Temperature sensor: is used to adjust the inner air temperature. It allows us to fill the structure with warm air in winter and vice versa in summer so that the surrounding area becomes more comfortable.

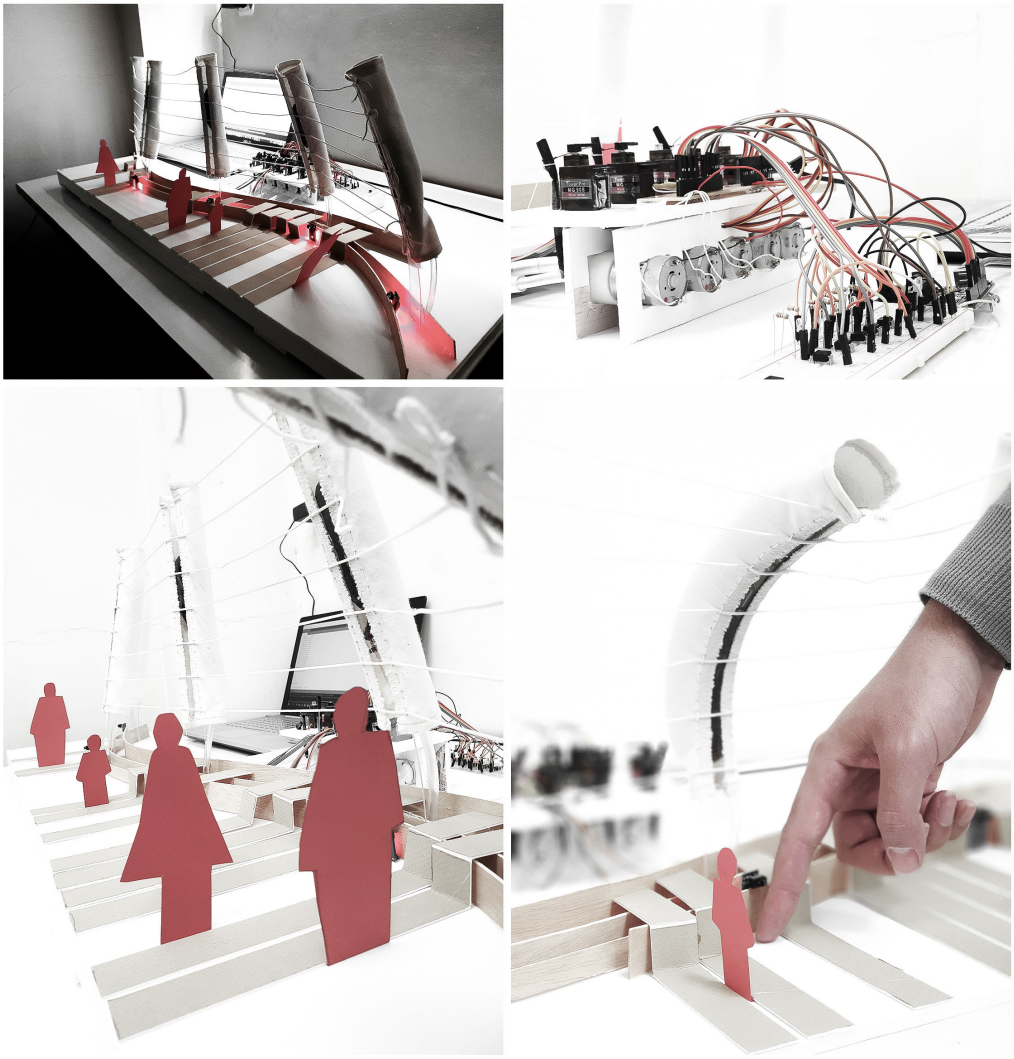
A video from the final model (Figure 8) is available on YouTube [3].

## CONCLUSION AND FUTURE WORKS

The result of this interdisciplinary study indicates that using soft robotics along with inflatable structures can create pleasant and satisfying spaces that can respond to human needs properly. Flexibility and softness are keys to creating these user-friendly responsive structures. They are low-cost and relatively durable and can be easily prefabricated and deployed in every environment. The structure is very light and malleable so it can be simply contracted after use and delivered to other sites. The application of this study can be expanded to larger scales, different organizations and with the use of other soft robotics technologies. For further research on this topic, we suggest a deeper study of durable materials which can be used outdoor and experimental test in 1:1 scale. Moreover, the sustainability of these systems has yet to be explored and developed.

We believe that soft robotics principles and mechanisms have a great potential to be implemented in architecture. It is a novel and fast-growing field, so close collaboration between architects and researchers in other disciplines like mechanical engineering, chemical science and etc. is essential.

Figure 8
Photos of the final 1:15 model. It was not possible for us to fill the whole path with columns, so to represent the core idea, we have created only 5 functional columns in this model.



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# Precision Partner

## *Enhancing GFRC craftsmanship with industry 4.0 factory-floor feedback*

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*This paper presents a novel human-machine collaborative approach to automatic quality-control of Glass-Fiber Reinforced Concrete (GFRC) molds directly on the factory floor. The framework introduces Industry 4.0 technologies to enhance the ability of skilled craftsmen to make molds through the provision of horizontal feedback regarding dimensional tolerances. Where digital tools are seldom used in the fabrication of GFRC molds, and expert craftsmen are not digital experts, our implementation of automated registration and feedback processes enables craftsmen to be integrated into and gain value from the digital production chain. In this paper, we describe the in-progress framework, Precision Partner, which connects 3d scanning and point cloud registration of geometrically complex and varied one off elements to factory floor dimensional feedback. We firstly introduce the production context of GFRC molds, as well as industry standards for production feedback. We then detail our methods, and report the results of a case study that tests the framework on the case of a balcony element.*

**Keywords:** *3d Scanning, GFRC, Feedback, Automation, Human in the loop, Digital Chain*

## INTRODUCTION

The construction Industry is the second least digitized in the world [1]. Despite the increasing ubiquity of digital tools within design, simulation and management workflows (Claypool et al. 2019), most fabrication, assembly and construction practices rely on hand-work and craft expertise, whether in factories or on-site. This gap becomes relevant in the case of projects that involve complex geometries, in which dimensional feedback and quality control is central. While automated quality-control processes have been long established in production lines (Matt et al. 2020) to inspect for faults in high-volume production, implementing registration and feedback processes in hand craft shop-floor environments, the typical mode of production in the building industry, to inspect geometrically complex one-off elements remains a challenge.

Adapting Industry 4.0 technology to the factory floor would allow for skilled hand-craft processes to

be integrated with, and gain value from, the digital information chain. Skilled craftsmen perform central and critical roles in many manufacturing and construction processes, particularly within manufacturing tasks where the level of complexity and variation makes automation highly difficult or inefficient (Autor 2015). Within this type of manufacturing activity, human craft skills are able to contribute dexterity, flexibility, sensory and decision-making ability [2], and are recognised to outperform current autonomous and automated systems (Autor 2015). Because of this, it is important to understand how current Industry 4.0 research can extend beyond its current focus of establishing connections between machines and systems, and to consider the human in the loop. In this paper we explore how Industry 4.0 can enable new types of interface between craft expertise and digital design information through the idea of digital assistance, and the proposition that coupled human-automated activities can assist expert craftsmen in becoming even more effective and efficient.

In this paper, we describe a framework for automating feedback processes from 3d scanning to assist craftsmen in evaluating the geometric quality of their work. We contextualise our research through description of a specific manufacturing process - GFRC manufacturing - and against analysis of state of the art in production feedback. We introduce a new, prototypical framework in the context of expert mold makers creating molds for precast fiber-reinforced concrete building elements. Through feedback from 3d scanning, this framework enables craftsmen to assess their production against digitally established critical dimensions at any point throughout the making process, and to make spot measures that they would not be able to perform via physical measuring techniques. The prototypical framework aims towards a seamless solution, with the objective that automation should reduce any disturbance of the making process to a minimum, so that gaining feedback does not require expert knowledge. Key aspects of this ambition are the development of registration protocols and the creation of a customised interface. The framework is developed and evaluated in an interdisciplinary collaboration of researchers from CITA, GFRC producer BBFiberbeton and the metrology provider TickCAD.

## MANUFACTURING ARCHITECTURAL GFRC ELEMENTS

Within architecture, GFRC is used to manufacture lightweight, prefabricated cladding elements, facade panels, and balconies with varying forms and shapes [3]. GFRC elements can be categorised along a scale of increasing geometric and manufacturing complexity as either rectilinear, faceted and free-form, and their manufacture requires a series of stages to be connected together. The typical process of manufacture starts with an analysis of the client's input data (2d CAD or 3d BIM), detailing and optimisation of the design according to budget, manufacturing and other constraints and the definition of quality criteria for the later element, including surface quality and tolerances in dimensions.

In a second stage - process planning - the mold is designed and drawings of its parts are generated. Most molds are made from flat sheet materials, combining wood and plastic, cut to shape (Fig. 1). Because of the high variability in GFRC element design, and resultant high geometric variability design, making and assembling of molds is not automatised and the resulting quality relies on the skills of craftsmen. In order to effect overall cost and efficiency the design of GFRC elements and molds is tweaked, so that a mold can be reused many times or easily adapted to changing geometries in the production of an element.

The 25% of molds at our industry partner, which are faceted or free-form are more challenging, as 2D drawings can fail to describe the complexity of the form regardless of the number of details included. Here, CNC routing can be used for the production of curvilinear sub elements of molds or the 3d milling of entire mold surfaces (Kreysler, 2017).

Finally GFRC is sprayed in layers into the mold and rolled a handheld roller (Fig.1), which requires high level of craftsmanship again, since the strength of the concrete is determined from the correct mixture and compacting the concrete slurry with the fibres (Brandt 2020).

Quality Control is imperative at all stages of production. At two stages geometric discrepancies between the built mold and its specification are measured: 1) during the manufacturing of the mold and 2) after finishing the element. The use of contact-type measurement devices (ruler & tape measures) determine the achievable precision and type of measurements. Complex mold geometries limit their use. The permissible geometric discrepancies between designed and built vary with the type of building elements. Façade elements require relatively high precision, especially in the position of mounting points (aim: functioning attachment), and for edges of elements (aim: aesthetically pleasing gap dimensions and alignment with adjacent elements). The tolerances for length are: +-3mm for elements < 3m, +-5mm for elements < 9m, and 8mm for linear straightness (Kim et al. 2020). Others quality aspects, like straightness and squareness, have higher permissible tolerances and are in practice hardly measured.

The above workflow shows a disconnection between the physical production and the digital element specification since the whole manufacturing process relies on the moldmaker's execution of 2d technical drawings.

Figure 1
Mold building and mold casting, both specialized hand craft processes

## STATE OF THE ART IN PRODUCTION FEEDBACK

The quality of the finished GFRC element is dependent upon the quality achieved in each of the steps from design to fabrication. According to the NRC (National Research Council 1995) the ability to produce quality products hinges on four key competencies: modeling of process form and precision levels, design tolerancing of parts and products, selecting production processes that match part specifications, and applying quantitative measurement methods for inspection and process control. The first two-process modeling and design tolerancing-are of primary importance and drive the second two. The first three take place pre-production, while inspection can only take place during and post production.

The field of manufacturing engineering has developed multiple approaches to ensure and improve quality and efficiency in production. A crucial element is early and repeated testing and feedback at each stage of development and production of elements (Matisoff 1986) . This feedback can be organised within a single organisational level of production (Horizontal Control Loop) or between multiple organisational levels (Vertical Control Loops) (Schmitt et al. 2011). Horizontal Control describes how one process is being controlled and how this control loop interacts with other control loops (e.g. end-of-line inspection on shop floor level) Vertical Control describes a multi-scalar approach of how control loops of lower levels are monitored, controlled and designed (e.g. management assessment of business processes). The need for higher quality production methods, which can adapt quickly to changes in production and are efficient at minimal batch sizes - as in the call for an Industry 4.0 (Kagermann 2015) - has led to an extension of thinking about quality control in industry. This expands consideration to include 1) the organisational level, where feedback is extended to span customer, production and design in Closed-Loop Quality Systems [4], 2) temporal aspects, with an urge for continuous and real time feedback on human and machine processes (Even-Chaim 2019) and

3) the further development of flexible manufacturing systems (De Toni & Tonchia 1998). These last items resonate with research in architectural construction exploring online feedback systems for robotic manufacturing with (Sutjipto et al. 2018) or without humans in the loop (Nicholas et al. 2017).

The triggering moment for feedback in any quality loop is the act of data generation, the registration of the measured data to a reference model and the analysis and feedback of deviations between these (Martin Tamke et al. 2016).A vast array of large-scale metrology technology exists for the capturing of dimensional data(Peggs et al. 2009). Ìn the context of GFRC manufacturing, this list is narrowed down to fast, contactless and mobile techniques 3d Laser Scanner and Digital Photogrammetry. This is due to the specifics of GFRC production:

- Large dimensions, weight, complex geometry with few geometric features, undercuts, narrow spaces and uniform color of molds and GFRC elements
- Small batch size of production runs, which requires frequent 3d capture
- Dusty production environments - necessity to move gear gear off site, when not in use
- Financial constraints, require measurements to be carried out by production floor personnel (need for ease of use and high automatisation)

Both Laser Scanners and Digital Photogrammetry provide sufficient precision to match the minimal production tolerances of casting (1mm) (National Research Council 1995) and the required tolerances in the construction industry (M. Tamke et al. 2014). Laser Scanning is used in research for control of surface qualities in concrete production (Puri & Turkan, 2016; Wang et al. 2016) and onsite control of rebar and concrete formwork (Kim et al. 2020).

Once scan data is generated, it needs to be processed to enable dimensional feedback. However related industrial products [6,7], are generic tools made for use in mechanical industries. In order to achieve the required precision, these products must be operated by specialists who adapt the measurement to the specific object, postprocess data and execute deviation control in separate specialist software packages. And while technological developments allow for a high degree of automatisation in the registration of large sets of point cloud data (Chen & Medioni 1992; Ochmann et al. 2014; Schnabel et al. 2007), the automated analysis of dimensional deviations remains a field of research (Martin Tamke et al. 2016).

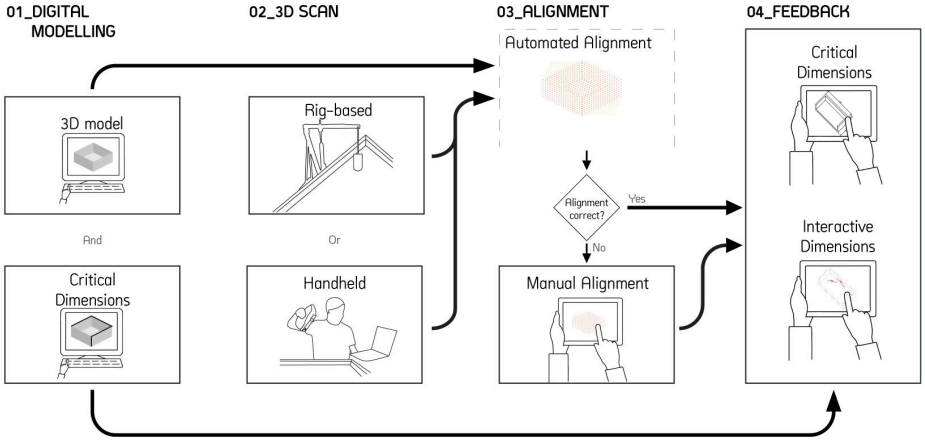
## METHODS

In this paper we present a new, prototypical framework, termed Precision Partner - that enables the craft practice of mold-makers by establishing an automated connection to precise, digital information. In the previous section we have established the requirements for this novel approach to horizontal production feedback.

The workflow is established through software and hardware prototyping in direct dialogue and discussion with industry partners. We also develop a larger research methodology for industrial research collaboration, concerning real-case data gathering, quick Design/Development/Testing and feedback and engagement with the craftsmen and engineers to guide development and testing. Each software and hardware implementation is evaluated for its independent functionality and also for fit into the Precision Partner framework as a whole.

The development of the framework (Fig. 2) is guided by and tested against three main criteria. **First, the Precision Partner framework needs to be open-ended**, where components can be continuously added. This reflects the high level of variability in GFRC manufacture. A digital baseline approach, to handle incoming project information and generate construction information, as well as set the stage for registration and deviation feedback, is at the core of the framework. **Second, the framework necessitates an easy integration with existing production pipelines without too much disruption for the business**. For instance, differently from industrial product manufacturing, GFRC molds are made in

Figure 2
Relationship between the digital components and the human activities in the Precision Partner. Variability of the types of human interaction - station based, physical (3d scanning) and on the fly.




an adaptive production context, where the factory facilities provide a flexible production sequence, rather than a standard production chain, depending on the size and amount of elements to be produced. This is why we develop multiple flexible scanning scenarios. Finally and most importantly, **the framework needs to be accessible to a workforce without specialized computer skills**, since it will be used by shop-floor craftsmen. We design a simple interactive UI for on-the-fly dimension check, where the data processing is fully automated, allowing the craftsman to easily assess the quality of a component and react to any deficiencies. We expand upon the technicalities of each of these three development criterions in the sections below.

### *Digital modelling*

The core of our production feedback lies in being able to compare the real element, to it's digital representation. For that, we require a standard set of outputs: The geometry of the mold or casted element in ply, with the geometry oriented orthogonally in XYZ space, as well as a list of the critical dimensions that need to be checked, such as height, length, width and thickness. We accommodate for element variability while ensuring a baseline quality. In fact, since element design and specification comes in different data formats from one project to the other, we develop input pipelines specific to different 3d model formats. However, when the GRC element is rectilinear and geometrically simple the input data from the client is provided as 2d drawing. As these are not fitting to a 3d approach, they require heavy manual editing in order to create consistent quality and labeling. We therefore develop a parametric configurator. This produces from simple numerical inputs,both a 2d technical drawing set and a cutting list to build the mold, as well as the necessary 3d model of the element and the mold. This drastically increases design-to-production productivity and guarantees consistent data quality for the following operations. It also allows very easily to create partial digital models, to compare against partial digital scans during the mold-building process.

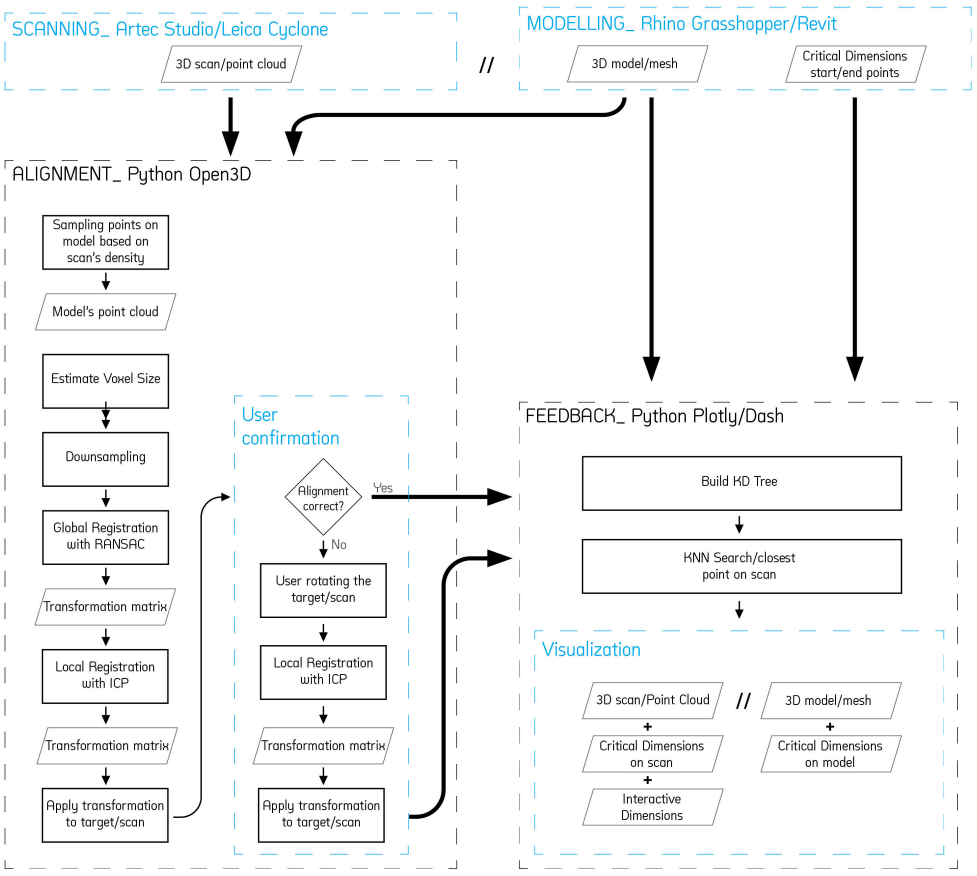



Figure 3
Back-end cloud processing workflows: processing of the acquired phyisical scan, alignement with digital model, comparison and feedback

### *Scanning Protocols*

Horizontal feedback on the factory floor requires flexible scanning protocols in order to be minimally disruptive to the ongoing production chain. At different instances of the production, different parts of the mold can be scanned to check the quality of the built piece. Later, the whole mold can be checked prior to casting, and the element can be checked after unmolding. For that we develop two different scanning scenarios: partial or small scans and complete scans.

**Partial Scans - Handheld.** Handheld scanners operate through structured light. By shooting up to 16 frames per second, they are able to reconstruct the surface they are scanning on the fly using photogrammetry. Their use by craftsmen requires little training. Scans can be made of specific edges, or specific mounting points, which then feed into the registration workflows described below. A craftsman can also use printed trackers to check for a specific dimension of interest, that could be hard to measure

with a ruler for example. We envision that these scans would be used for fast intermediate checks during the mould building process.

**Complete Scans - Rig Based.** Lidar scanner.capture large areas quickly. This allows for a complete scan of the mold during manufacturing or for a final quality control. We build a rig with a suspended 3d scanner, which can be operated by a craftsman and positioned over the mould. The data is then passed to the registration workflows we describe below.

### *Cloud Processing Workflows*

In order to give feedback on dimensions, the entire or partial scan, must be registered to its 3d model. We develop a workflow (Fig.3) for automatic registration using the Open3d library for Python (Zhou et al. 2018). The workflow uses a combination of RANSAC (Schnabel et al. 2007) algorithm for global registration and ICP (Chen and Medioni 1992) We prepare the point clouds of the scans through noise removal using nearest neighbour algorithms. We subsequently analyse the density of the scans and generate a point cloud from the 3d model with similar density, as this improves the success rate of the registration drastically. Since Ransac relies on an initial random seed, the results are previewed in the UI for confirmation. In the case of miss-alignment (currently at 5% of cases, but protocols are being developed to improve this) we developed a fallback manually-aided alignment based on matching the bounding boxes through simple slider-based operator inputs. The transformation matrix is applied to the scanned cloud to match it to the 3d model, allowing critical measures to be calculated on the scanned cloud using nearest neighbour search based on the baseline model. These workflows are all computed in the back-end and need under 1 minute computing time.

### *UI for precision feedback*

To guarantee accessibility of this tool, the whole workflow is wrapped into a simple User Interface (UI) built using Dash library for python [8]. The UI runs on a web browser, and is built for interactive queries. At startup, the operator selects the project folder, in which cloud scan and 3d model are saved. The tool displays the pre-defined dimensions for both the scan and the model, and flags dimensions that are beyond tolerance. The operator can then use the spot-check feature to add additional dimensions, and better diagnose the problem.

## WORKFLOW EVALUATION BALCONY CASE STUDY

In order to evaluate the performance of our workflow, we test it against a recurring type of element at our industry partner: The balcony panel type. These present a rectilinear base with edges on 3 sides. The case study in question measures 2554x1297 mm and is 170mm deep with a 12mm thickness. The edges are at 90 degree with respect to the base, but present a chamfer feature. The panel requires a 3x6 grid of metallic mounts. The parametric configurator generates a 2d technical drawing set, as well as mold cutting list for the mold builders. It also generates a 3d model of the element, and a 3d model of the mold (Fig. 4). We export these models and the critical dimensions to the Open3d workflow. The element mold is scanned both entirely and partially (Fig 5). Scans are processed as described in the section above. We generate a model point cloud consisting of approx. 3.5million points to match an approx. 4 million point scan. We test two registration methods on both partial and full scans, a fully automated one using Ransac and ICP and a manually augmented one (Fig 6). The latter utilizes trackers to create two sets of correspondence points. This is accomplished through the calculation of distances between the three points for each set and the forming of a sequence (e.g. p1 corresponds to p1', p2 corresponds to p2', etc.). After that, a transformation matrix is created in order to match the two point sets and it's applied to the scan. Through this the scan and the model are roughly registered. Finally, ICP is used for local refinement. The critical dimensions are computed on the UI (Fig 7) and the operator can visualize and interact with them.

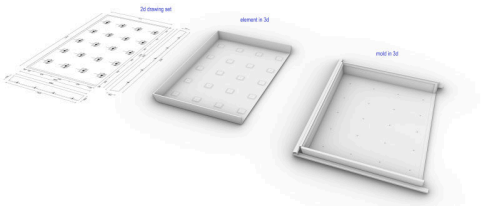



Figure 4
Outputs of the mold configurator parametric algorithm

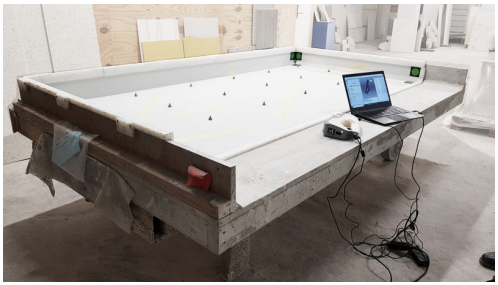


Figure 5
Scanning of a balcony type mold using Artec3d Eva handheld scanner

## DISCUSSION

The conducted experiments have revealed that the relationship between 3d scan and 3d model is the cornerstone of the workflow. In order to be able to register the scans to its 3d model, they need to be of similar nature. We have found that the geometric features of the element have a big impact on the success of the registration algorithm. Full automation is successful when there is a 70-100% correspondence between the point clouds. Partial scans with less than 50% correspondence will require partial models to be registered to. This is possible when the model is generated from the parametric configurator. While being a theoretical use case this would allow to produce assembly sequence models, to be able to check at steps in the mold building process.

## CONCLUSIONS AND FUTURE WORK

In this paper, we have described research towards a new framework for factory floor quality control that considers the human in the loop. The framework introduces Industry 4.0 technologies to enhance skilled craftsmen in the making of molds through the provision of horizontal feedback. It allows a craftsman to assess the geometric accuracy of their work against a digital model on the factory floor, through 3d scanning-based feedback of either pre or user-defined dimensions and deviations. This framework is tested through the case of a balcony element, where correspondence is found to be a key factor in successful automation.

As the paper details, the seemingly straightforward activity of gaining dimensional feedback via 3d scanning is found to require a wider, coordinated set of digital workflows. To achieve these for the high level of geometric complexity and variety that characterizes GFRC production, and with non-expert users rather than a skilled on-site technician, requires that the framework be both automated and open ended.

Automation is used to ensure the relationship between 3d scan and 3d model. An automated mold configurator tool is developed to enable a baseline for comparison between 3d model and point-cloud. A fully automated headless workflow correlates 3d scans made by either handheld or rig based scanning tools against a 3d model, using RANSAC and ICP algorithms. If needed, alternative workflows offer user input.

Open Endedness is achieved by constructing the framework as components. This enables different input pipelines, different modes of 3d scanning best suited to different mold geometries, extents of scanning, and registration either during or at the end of the making process. Here, further work is currently being undertaken to better enable the use of partial scans through specification of partial models, as a means to address the issue of correspondence in the registration of in-progress work. The question of when feedback can occur can be linked to the question of how feedback can be provided. Here, future work is planned to extend the framework to incorporate visual spatial feedback through overlay of point-cloud, model, deviation information and real world data through augmented reality.

Figure 6
Results of two registration processes of 3d model and scan: Upper two images - Fully automated RANSAC and ICP. Down two images - Manually augmented Correspondence points and ICP.

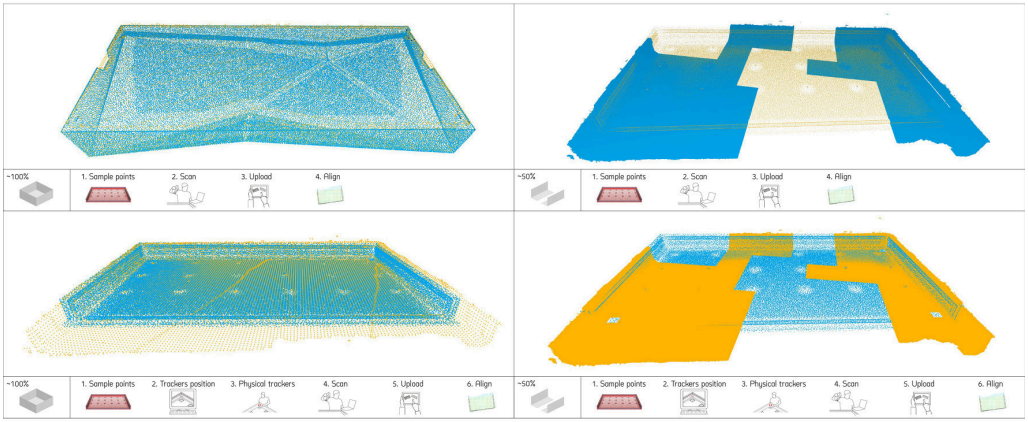
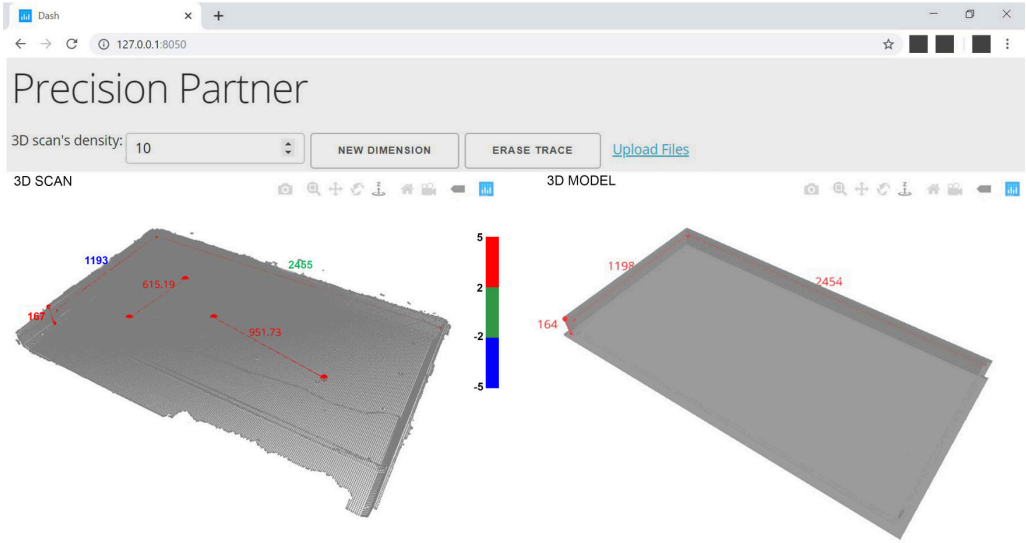



Figure 7
Our UI displayed on a web browser



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# Extending the Passive Actuation of Low-tech Architectural Adaptive Systems by Integrating Hygroscopic and Thermal Properties of Wood

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*Recent studies involving the passive actuation of zero-energy architectural adaptive systems using programmable materials have addressed the prototyping of wood motion responses by utilizing its latent hygroscopic properties. Most of these systems have focused on mechanisms that are triggered by varying levels of humidity, with very limited efforts addressing the effect of temperature variations; a challenge in hot climatic zones. This paper extends the passive actuation of adaptive systems in climates where humidity and/or temperature variations are dominant. A series of physical experiments were conducted to observe wood veneer sample deflection and motion response behavior under three varying temperature and humidity conditions, with constant values of fiber orientation, lamination, thickness, type of wood, and sample proportion and geometry. The experiment results showed that the coefficient of thermal expansion is an effective parameter, where higher deflection and response speed was recorded under high relative humidity (>80%) upon increase in temperature (>35°).*

**Keywords:** *Programmable materials, Adaptive facades, Hygromorphic behavior, Responsive systems, Shape-shifting*

## INTRODUCTION

Programmable materials are progressively replacing mechanical systems through encoding their latent properties to achieve passive controlled motion response to external stimuli such as humidity and temperature, thus acting as zero-energy low-tech architectural adaptive systems. Several studies have addressed the programming and prototyping of wood motion response using physical experimentation (Correa et al., 2015; Holstov et al., 2015; Wood et al., 2016), testing wood response in real weather conditions (Menges and Reichert, 2012; Krieg et al., 2014), and using numerical simulations to estimate wood motion response (Rüggeberg and Burgert, 2015; Abdelmohsen et al., 2019).

Hygroscopic properties of wood are related to its ability to absorb and hold water causing swelling and shrinking upon water release. The ability of wood

to absorb and retain moisture content is related to wood grain orientation and type of wood (Forest Products Laboratory, 2010). Different responses of wood to humidity enable a specific programmability logic that can be utilized in adaptive architectural systems. Most systems have relied however on exploring mechanisms activated by fluctuating levels of humidity, with limited efforts related to the effect of temperature variations on the resulting actuation.

This paper attempts to extend the passive actuation of adaptive systems in climates where humidity and/or temperature variations are dominant. We conduct a series of physical experiments using Beech veneer samples. We observe sample deflection and motion response behavior upon three temperature and humidity conditions, and varying parameters like fiber orientation, thickness, proportion, lamination, geometry, and type of wood. We use the Kinovea image tracking software to compute angles of deflection, time duration and response speed.

## HYGROSCOPIC BEHAVIOR OF WOOD

Hygroscopy generally describes the ability of a material to absorb moisture (absorption) and release moisture (desorption) from the atmosphere so that a relatively balanced environment is constantly preserved. Water molecules are absorbed primarily inside wood in cellulose and hemicellulose tissues, in a state known as bound water. The moisture content in wood, calculated according to the weight of water and the wood substance, ranges between 27-30 percent of its fiber saturation point (FSP). Within this state, the maximum amount of bound water is absorbed, and any moisture is simply stored in cell cavities, in a state known as free water.

Compared to bound water, free water has only a small impact on the mechanical characteristics of timber. Nevertheless, reducing the binding water decreases the gap between cell tissue microfibrils, thus contributing to a significant change in the proportions and mechanical intensity increase due to interfibrillar bonds. Therefore, the physical changes in wood (as an example of any anisotropic substance) has three distinct coefficients: (1) longitudinal shrinkage (or grain parallel), which is typically minimal (2) tangent to rising rings, exhibiting major shrinking, and (3) radial shrinkage stretching from the middle of the stem to the bark (Reichert, Menges & Correa, 2015).

Equilibrium moisture content typically takes place upon the process of absorbing moisture from the surrounding atmosphere when dry but correspondingly moisturizing when wet, thereby maintaining a moisture content that is balanced with the water vapor intensity of the surrounding atmosphere. Therefore, for every combination of vapor pressure and atmospheric temperature, there exists a corresponding moisture content of the wood so that the vapor does not spread inward or outward. This humidity content is known as the equilibrium moisture content (EMC). The use of relative humidity rather than vapor pressure is generally more practical. Relative humidity is described as the percentage of the air partial vapor pressure to the saturated vapor pressure. (Dinwoodie, 2000).

## THERMAL BEHAVIOR OF WOOD

Wood, similar to other materials, undergoes physical transformations that are directly proportional to increased temperature. This is due to an increase in spacing between wood molecules as they improve the vibration magnitude at rising temperatures. These motions are typically evaluated for practical purposes as a coefficient of linear thermal expansion and quality for certain wood types (Dinwoodie, 2000). The pattern of wood expansion upon temperature increase is linear over a wide temperature ranges. Minor differences between both the radial and tangential planes of expansion are generally ignored. The dimensional changes in wood caused by temperature differences are relatively small compared to changes in sizes resulting from moisture uptake or loss. If timber has a moisture content of higher than 3%, shrinkage due to humidity loss in heating is higher than the thermal expansion and the

net dimensional shift in heating will be negative, as shown in figure 1 (Dinwoodie, 2000).

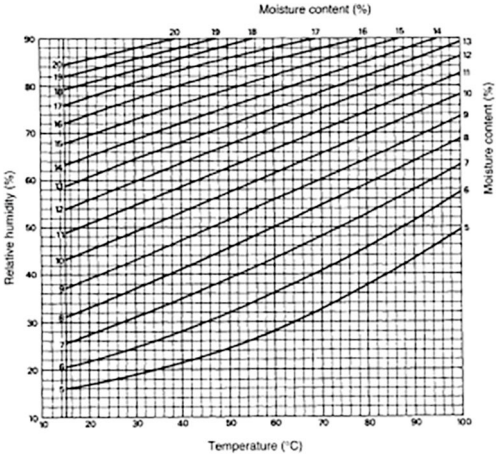



Figure 1
Relationship between the moisture content and temperature of wood at a specific relative humidity (Dinwoodie, 2000)

The coefficient of thermal expansion of wood is a function of the relative change of proportion caused by change in temperature. Coefficients of thermal expansion of fully dry wood are strong across all directions which expand with heat and contract upon cooling. Work on the effect of wood material variance on temperature change was typically performed in limited quantities. The value of thermal expansion of overdry parallel wood grain appears to be independent of specific gravity and organisms (Laboratory, 2010).

## RELEVANT WORK

Typically, if there are significant changes in the temperature of the environment, this results in deformation changes, due to an increase in the associated humidity by shrinking and swelling, which exceeds small thermal expansion and contraction values independently. Dimensional changes induced by temperature variations are negligible for the daily use of wood (Hoadley, 2000).

Although expansion is not normally significant, the influence of temperature on wood strength is essential. High temperatures may result in both temporary and permanent decreases in timber strength. Also, net effects depend on factors such as wood type, moisture content, heat sources and the level and time interval of the heat (Hoadley, 2000). With the configuration shown in figure 2 for example, it was possible to achieve a full opening of the mechanism in under 3 minutes, while the closing process time was reduced to only 12 minutes (Reichert, Menges & Correa, 2015). In this example, a steam-based humidifer and a radiation source was used to accelerate the reaction time of the wood sample.

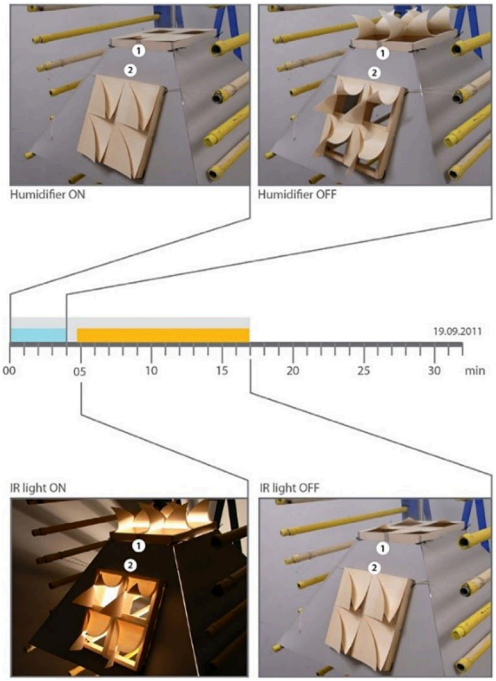



Figure 2
Using a steam-based humidifier and a radiation source to accelerate the responsive reaction time (Reichert, Menges, & Correa, 2015)

Although local thermal radiation affects the reactive behavior of wood veneer by influencing relative humidity, air convection temperature changes generate more general and stratified alteration. Furthermore, the relative humidity of the atmosphere can be improved without excessive moisture input, as shown in figure 3 (Reichert, Menges & Correa, 2015).

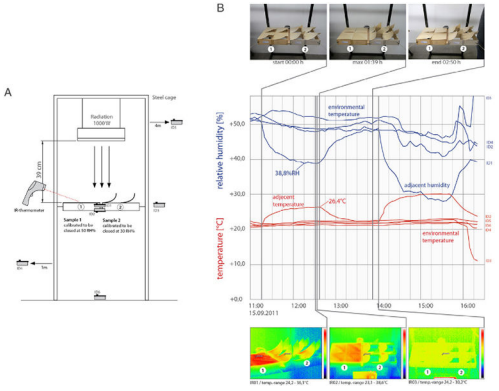



Figure 3
Experimental setup through the radiation source (Reichert, Menges, & Correa, 2015)

## APPROACH

The effect of temperature on wood veneer generally differs from the effect of humidity on the same sample. We first conducted two pilot tests to understand and delineate the basic effect of each of temperature and humidity on wood veneer samples. Based on precedents from the literature, it was demonstrated that temperature can influence the material by means of enlarging the porosity level of the materials so that it can gain more moisture. This can be conducted through either increasing ambient air temperature or by applying direct sprayed water with varying water temperature. Figure 4 illustrates the bending effect on a wood veneer sample upon applying both hot water spray and tepid water spray. Larger deflection was observed with the hot water sprayed sample.

The second pilot test demonstrates the effect of both humidity and temperature on the same sample. As shown in figure 5, upon applying and increasing humidity on the sample, the exposed surface acts as an active surface by swelling directly based on the amount of humidity applied. Upon increasing the temperature only, the exposed surface shrinks, implying that the porosity level increases while having a little amount of moisture. This results in a deformation in the sample in the loose surface, in addition to decreasing the amount of moisture of the exposed surface due to increasing the temperature level.

In the following sections, we demonstrate three main experiments that were conducted under specific wood parameter conditions and three varying humidity and temperature conditions: (a) varying humidity and constant temperature, (b) varying temperature and constant humidity, and (c) varying humidity and temperature. For the basic setup, we used a sealed chamber for the containment of the wood samples, and a vertical clamp fixed on a horizontal plane to avoid friction. The clamp allowed for free motion from one end. A digital camera was used to record the motion of wood using video and time-lapse images. The average deflection and response speed rate were recorded for each experiment. Each wooden sample was marked with markers to evaluate the deflection angle using the Kinovea image and video analysis software.

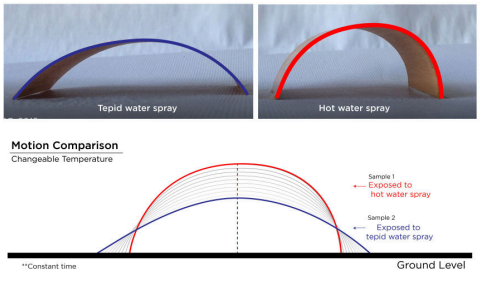



Figure 4
Motion comparison between two wood veneer samples, one with hot sprayed water and the other with normal tepid water

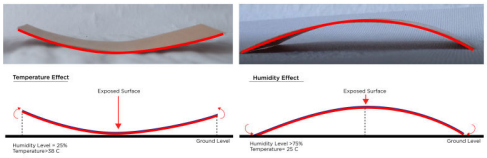



Figure 5
The effect of both humidity and temperature on wood veneer sample motion. Left: increasing temperature, Right: increasing humidity level

Kinovea is a free image analysis software that is used to monitor and track motion through live analysis of linear and angular measurement per frame by means of defining fixed and movable markers. Its validity and reliability has been previously verified (Adnan et al., 2018). In addition, it was previously used

to track and record the response of wood to humidity (Abdelmohsen et al., 2018; El-Dabaa et al., 2020). We use Kinovea in this paper to record videos for each of the three experiments, to monitor and measure the resulting angles of deflection upon varying humidity levels, and to calibrate measurements.

### *Experiment 1: Varying humidity and constant temperature*

In this experiment, a Beech rectangular sample with dimensions 14x7mm was exposed to three conditions of humidity (Low 60%-65% RH, Medium 70%-75% RH, and High 80%-85% RH), while the temperature was kept constant at an average of 25 degrees Celsius. The sample was a single-layered 0.5mm-thick radial cut with 0 degrees fiber orientation. Table 1 shows the basic experiment setup, temperature and humidity readings, and the recorded angles of deflection in each of the three cases.

Based on the applied conditions of varying humidity under constant temperature, as shown in table 2, the experiment demonstrates that the sample reacts to humidity with an average motion response rate of 15.4 degrees/minute and a maximum of 105 degrees of deflection, with a gradual motion of transformation (58 degrees of deflection at 63%

Table 1
Response of wood veneer sample exposed to room level temperature (24.5 - 26.4 Celsius) and three varying conditions of relative humidity (60%-65% RH, 70%-75% RH, and 80%-85% RH)

| Temp | Hum. | Angle |
|---|---|---|
| 26.4 ℃ | 63 % | 58 ° |

Column (1)

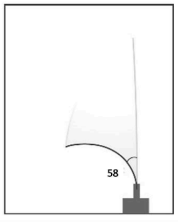
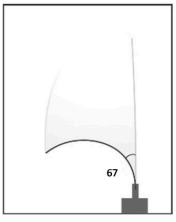
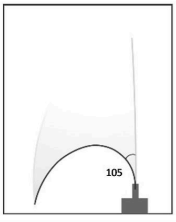
| Temp | Hum. | Angle |
|---|---|---|
| 26.0 ℃ | 71 % | 67 ° |

Column (2)

| Temp | Hum. | Angle |
|---|---|---|
| 24.5 ℃ | 85 % | 105 ° |

Column (3)

Table 2
Parameters and observations of wood veneer sample exposed to room level temperature (24.5 - 26.4 Celsius) and three varying conditions of relative humidity

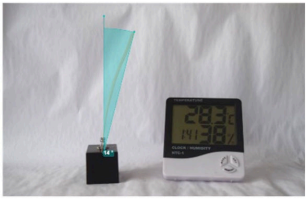
| Parameter | Sample | | Reactions | | |
|---|---|---|---|---|---|
| | | | RH (60-65) % | RH (70-75) % | RH (80-85) % |
| Increasing Humidity | Veneer | Beech |   |   |   |
| | Dimension | 14x7 mm | | | |
| | Temp. | Varies -Avr. 25 C | | | |
| | Thickness | 0.5 mm | | | |
| | Grain Angle | 0° Degree | | | |
| | Cut | Radial | | | |
| | Humidity | Increasing | | | |
| | Type | Natural | | | |
| | Shape | Rectangular | | | |
| | Layering | Single Layer | | | |
| | Average Motion Response Rate | 15.4 Degree/min | After 2 min. Response rate: 29 degrees/min | After 4 min. Response rate: 16.75 degrees/min | After 10 min. Response rate: 10.5 degrees/min |

RH, achieved after 2 minutes at a response rate of 29 degrees/minute, 67 degrees of deflection at 71% RH, achieved after 4 minutes at a response rate of 16.75 degrees/minute, and 105 degrees of deflection at 85% RH, achieved after 10 minutes at a response rate of 10.5 degrees/minute). The primary observation in this experiment is that, based on the principle of equilibrium moisture content (EMC), there was a noticeable change in motion of the sample based on its absorbable nature.

### *Experiment 2: Varying temperature and constant humidity*

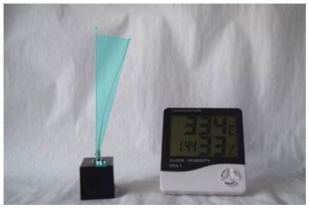
In this experiment, a Beech rectangular sample with dimensions 14x7mm was exposed to three conditions of temperature (Low 28.3 degrees Celsius, Medium 33.4 degrees Celsius, and High 40.0 degrees Celsius), while the humidity was kept relatively similar (average of 33% RH). The sample was a single-layered 0.5mm-thick radial cut with 0 degrees fiber orientation. Table 3 shows the basic experiment setup, temperature and humidity readings, and the recorded angles of deflection in each of the three cases.

Table 3
Response of wood veneer sample exposed to three levels of temperature (28.3, 33.4 & 40.0 degrees Celsius) and an average of 33% relative humidity



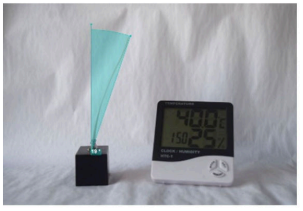
| Temp | Hum. | Angle |
|---|---|---|
| 28.3 °C | 38 % | 14 ° |

Column (1)



| Temp | Hum. | Angle |
|---|---|---|
| 33.4 °C | 33 % | 15 ° |

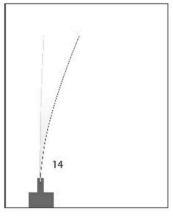
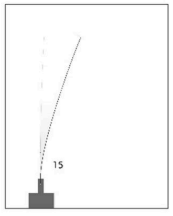
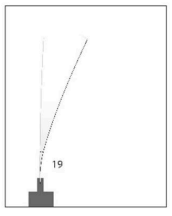
Column (2)



| Temp | Hum. | Angle |
|---|---|---|
| 40.0 °C | 25 % | 19 ° |

Column (3)

Table 4
Parameters and observations of wood veneer sample exposed to three levels of temperature (28.3, 33.4 & 40.0 degrees Celsius) and an average of 33% relative humidity

| Parameter | Sample | | Reactions | | |
|---|---|---|---|---|---|
| | | | Temp. 28.3°C | Temp. 33.4°C | Temp. 40.0°C |
| Increasing Temperature | Veneer | Beech |  |  |  |
| | Dimension | 14x7 mm | | | |
| | Temp. | Increasing | | | |
| | Thickness | 0.5 mm | | | |
| | Grain Angle | 0° Degree | | | |
| | Cut | Radial | | | |
| | Humidity | Varies – Avr.33 | | | |
| | Type | Natural | | | |
| | Shape | Rectangular | | | |
| | Layering | Single Layer | | | |
| | Average Motion Response Rate | 2.35 Degree/min | After 4 min. Response rate: 3.5 degrees/min | After 7 min. Response rate: 2.1 degrees/min | After 13 min. Response rate: 1.46 degrees/min |

Based on the applied conditions of varying temperature under relatively similar levels of relative humidity, as shown in table 4, the experiment demonstrates that the sample reacts to temperature with an average motion response rate of 2.35 degrees/minute and a maximum of 19 degrees of deflection. The samples reacts to the default temperature at 28.3 degrees Celsius normally and is deformed by 14 degrees of deflection, achieved after 4 minutes at a response rate of 3.5 degrees/minute. However, at higher temperatures (33.4 degrees Celsius), the sample is deformed by 15 degrees of deflection achieved after 7 minutes at a response rate of 2.1 degrees/minute. At 40 degrees Celsius, the sample is deformed by 19 degrees of deflection achieved after 13 minutes at a response rate of 1.46 degrees/minute.

The more the heat gained by the sample, the higher the fiber ability for hydro expansion. Based on the principles of the coefficient of thermal expansion of wood, it was shown that higher levels of temperature are significant parameters. While the impact on the material motion and degree of deflection was not as significant as the experiment with varying humidity, temperature was still shown to act as an important stimulus in the shape-shifting and deflection process of the sample.

### *Experiment 3: Varying temperature and varying humidity*

In this experiment, a Beech rectangular sample with dimensions 14x7mm was exposed to increasing relative humidity (ranging from 65% to 74% RH) and high temperature conditions (ranging from 37.1 to 38.5 degrees Celsius). The sample was a single-layered 0.5mm-thick radial cut with 0 degrees fiber orientation. Table 5 shows the basic experiment setup, temperature and humidity readings, and the recorded angles of deflection in each of the three cases.

Based on the applied conditions of varying both humidity and temperature simultaneously, as shown in table 6, the experiment demonstrates that the sample reacts to humidity 65% and 38.5 degrees Celsius with a deflection of 47 degrees, achieved after 2 minutes at a response rate of 23.5 degrees/minute. It reacts to humidity 71% and temperature 37.6 degrees Celsius with a deflection of 59 degrees, achieved after 5 minutes at a response rate of 11.8 degrees/minute. It reacts to humidity 74% and temperature 37.1 degrees Celsius with a high deflection of 147 degrees; the highest recorded in the three experiments, achieved after 10 minutes at a response rate of 14.7 degrees/minute.

This demonstrates the combined effect of humidity and temperature as two significant parameters in the shape-shifting process. The more heat gained for the sample, the more the ability of the

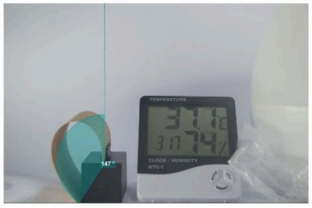
Table 5
Response of wood veneer samples exposed to high temperature (ranging from 37.1-38.5 degrees Celsius) and increasing relative humidity (ranging from 65% to 74%)

| Temp | Hum. | Angle |
|---|---|---|
| 38.5 ℃ | 65 % | 47 ° |

Column (1)

| Temp | Hum. | Angle |
|---|---|---|
| 37.6 ℃ | 71 % | 59 ° |

Column (2)



| Temp | Hum. | Angle |
|---|---|---|
| 37.1 ℃ | 74 % | 147 ° |

Column (3)

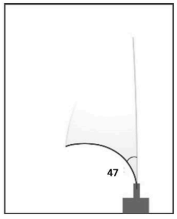
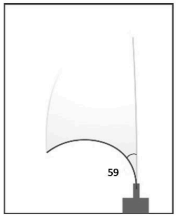
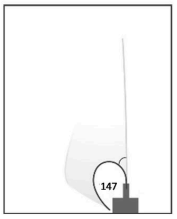
| Parameter | Sample | | Reactions | | |
|---|---|---|---|---|---|
| | | | Temp.38.5 – RH 65% | Temp.37.6 – RH 71% | Temp.37.1 – RH 74% |
| High Temperature & Increasing Humidity | Veneer | Beech |   |   |   |
| | Dimension | 14x7 mm | | | |
| | Temp. | High level | | | |
| | Thickness | 0.5 mm | | | |
| | Grain Angle | 0° Degree | | | |
| | Cut | Radial | | | |
| | Humidity | Increasing | | | |
| | Type | Natural | | | |
| | Shape | Rectangular | | | |
| | Layering | Single Layer | | | |
| | Average Motion Response Rate | 18.4 Degree/min | After 2 min. Response rate: 23.5 degrees/min | After 5 min. Response rate: 11.8 degrees/min | After 10 min. Response rate: 14.7 degrees/min |

Table 6
Parameters and observations of wood veneer samples exposed to high temperature (ranging from 37.1-38.5 degrees Celsius) and increasing relative humidity (65% to 74%)

fiber for hygro expansion, which allows the pores to gain more moisture. Accordingly, when humidity is applied, the sample could absorb more moisture than before raising humidity levels. This becomes one of the distinguishable characteristics of this hybrid sample.

## IMPLICATIONS ON FACADE MORPHOLOGY AND DESIGN EXPLORATION

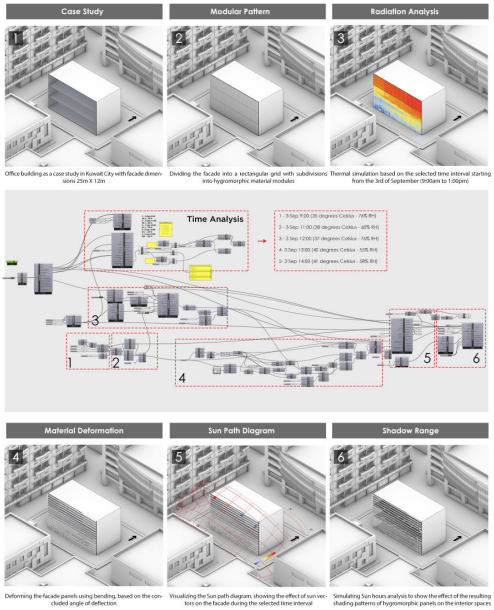
From the previous results, it is apparent that computationally the integration of temperature and humidity as two main input parameters introduces variations to the design exploration process of facade morphology, where two output parameters are basically in play: (1) shape-shifting (in terms of bending morphology, and (2) motion response rate. The implications on facade morphology and design exploration are therefore numerous. By modeling and simulating the effect of temperature and humidity on an arbitrary facade design in different climatic zones, a variety of design explorations and morphologies can be deduced. Variations of these designs can be introduced based on daily, monthly or seasonal simulation and predictions of hygromorphic responses.

Figure 6 introduces case study of an office building in Kuwait City with facade dimensions of 25m X 12m. Grasshopper was used to model and simulate the hygromorphic performance of modular facade skin panels based on weather data, using temperature and humidity as two main input parameters. The facade was divided into an orthogonal grid with subdivisions conforming with hygromorphic panels similar in proportion, fiber orientation and type of wood to the samples tested earlier. Thermal simulation was conducted in different time intervals and the resulting deflection morphologies and motion response rates were recorded. These morphologies were designed to conform with the concluded angles of deflection deduced from the pilot experiments such that the resulting morphologies respect wood response to different levels of temperature and humidity throughout the year. The script illustrates the effect of Sun vectors and shading patterns on interior spaces during desired time intervals. By studying deflection angles and response rates across the year, a more accurate representation of the design and behavior of facade panels can be embedded within the logic of the building skin configuration.

## DISCUSSION AND FUTURE WORK

The assumption at the beginning of the set of proposed experiments was that the process of passive actuation of low-tech architectural adaptive systems could be extended to include temperature as a significant parameter as opposed to only humidity. Based on the results and findings of the conducted physical

Figure 6
Case study of a hygromorphic facade skin configuration and responsive behavior based on incorporating temperature and humidity as two main input parameters




experiments in this paper, the added value of introducing temperature in this setting involves its role as a key regulator in the degree of deflection and motion response rate of the wooden samples.

As per the experiment findings, the nature of the deflection and motion response rate is affected by temperature in one of three states. In the first state, where temperature was kept at a constant and humidity was varied, the deflection occurred based on the absorbable capacity of the sample and its direct response to varying levels of humidity. In the second state, where temperature was varied, the deflection and motion response rate were more controlled and subtle. While the range of deflection varied between 58 and 105 degrees in the first state, it was shown to bend between 14 and 19 degrees in the second state. In the third state, where both temperature and humidity were varied, yet another pattern of deflection was observed, where temperature acted as a catalyst and accelerator for deflection and motion response rate, recording the largest deflection at 147 degrees.

Temperature - as a significant parameter - acts in this case as a key regulator of the shape-shifting process, and can be used to regulate the nature of deflection depending on the desired responsive skin morphology. Similar to the effect of active and passive layers in laminated wooden sample actuators, temperature is shown to play a role in accelerating, decelerating or stabilizing deflection of a given sample upon its response to varying humidity levels. By integrating both the hygroscopic and thermal properties of wood, a wide range of possibilities can emerge based on the extensive permutations and combinations of humidity and temperature as two interlaced significant shape-shifting parameters.

Another added value involves the domain of application of shape-shifting facades based on these findings. Most efforts to utilize hygroscopic properties of wood for adaptive facades relied on either a lab setting within sealed humidity chambers or less often utilizing outdoor air humidity in humid climatic zones. With temperature in the equation, shape-shifting responses can extend to include other climatic zones, including both hot arid and hot humid zones, where the mutual variations between humidity and temperature can result in emergent shape-shifting mechanisms.

Computationally, findings in this paper involve incorporating of temperature as a significant parameter in the shape-shifting process for low-tech adaptive facades using wood, added to typical parameters such as fiber orientation, lamination, layer thickness, type of wood, and ratio. This only opens the door for exploring the possibilities of resulting morphologies once the variation of temperature against these parameters is tested and investigated. A detailed exploration of these relations is expected to yield a rich vocabulary of deflection patterns, and motion response rates that exceeds the typical scenarios with humidity as the sole significant parameter.

Different scenarios of modeling and simulating these mechanisms and patterns can be conducted.

Parametric variations can be introduced in Grasshopper, as shown in the case study, to deduce morphologies needed for adaptive facade louvers or shading devices for example in hot arid or humid environments based on weather data. More sophisticated scenarios would incorporate numerical modeling tools such as COMSOL multiphysics software to predict deflection patterns, speed, orientation and direction based on actual temperature variations and their effect on wood in conjunction with humidity.

## CONCLUSIONS

Programmable shape-shifting materials are observed to suggest various deformations based on behavior. These materials can respond to environmental stimuli like radiation, humidity and others. Hygromorphic materials can be shaped with various transformations that are affected by the percentage of moisture in the air. This paper introduced yet another factor that affects hygromorphic material reaction, which is temperature. Temperature increases the hygro-expansion capability of a given sample. This can be regulated through multiple material parameters. A wide range of resulting motion types can be developed to induce different shape morphologies for adaptive building skins. This is considered extensive when compared to mechanically actuated systems that require complex fabrication techniques and high cost in terms of energy, time and effort to induce similar morphologies.

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# Use of a Digital Collaboration Tool for Project Review

## *A pedagogical experiment with multidisciplinary teams*

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*This paper emphasizes feedback from a pedagogical experiment in the context of teaching collaboration and design to multidisciplinary teams. A digital collaboration tool, a multi-touch table and collaboration software, was used as a support for discussion and decision-making for weekly project review meetings. The experiment participants' feedback on the use and usability of the digital collaboration tool highlights the potential for the use of synchronous collaboration technology and project-based learning for higher-level education. It also highlights the need for a transition towards implementation of digital tools at project review sessions.*

**Keywords:** *: Synchronous collaboration, Pedagogical experiment, Project-based learning, CSCW, NUI, BIM*

## INTRODUCTION

This paper is a part of a research on design and development of a prototype of a new collaborative decision-making tool, which would be well adapted to the AEC professionals needs, BIM workflow and collaboration practices. The development is guided by the user-centered design approach, which implies studies of the user's needs and behaviors.

The paper continues to explore the pedagogical experiment observations, data and feedback analysis that was partially presented in the previous work (see (Bolshakova et al., 2019)), which presented an overview of the users feedback and session documents from the first 2 phases of the experiment.

To complete the feedback summary, this paper also assists by integrating the lessons learnt into the future pedagogical approach.

The paper aims to: emphasize the feedback from the experiment participants on the use of a digital collaboration table in order to understand the current tool limitations and identify the requirements for future development; to emphasize the pedagog-

ical team feedback on the use of the touch-table for project review.

First, the section Experiment description introduces the pedagogical experiment of a digital collaboration table (DCT) use for synchronous co-located collective project review meetings (digital collaboration session or DCS). The DCT is a system of software: collaboration environment "Shariiing" developed by "Immersion"[1]; and of hardware: a PC and a multi-touch screen. In detail, the section describes the pedagogical context and the pedagogical experiment phases, also it provides a short overview of the collaboration tool and sessions.

The following section presents the research questions and tools, and it highlights the relevant to the usability feedback evaluation tools, which are emphasized in this paper in particular.

Next section of the paper summarizes the usability feedback on DCT from the sessions' participants, and it concludes with the pedagogical team reflection on the DCT use experience.

## EXPERIMENT DESCRIPTION

### *Fostering digital design and collaboration practices in AEC*

Collaboration and collective decision-making at project team meetings is an important part of any construction project development. At the meetings multidisciplinary cooperation and collaboration require an effort from all project participants (Staub-French and Khanzode, 2007).

In addition to the collaboration inside the project team aspect, nowadays digital tools and BIM are the standard for project development (Kensek, 2014). Therefore there is also a need for an efficient and AEC adapted digital collaboration environment (Achten, 2001), for a digital continuity of the workflow (Boje et al., 2019), and for a management of digital coordination in design (Whyte et al., 2008).

Thus, it is important to introduce the future AEC professionals to such collaboration and digital design practices during their studies.

### *Pedagogical context*

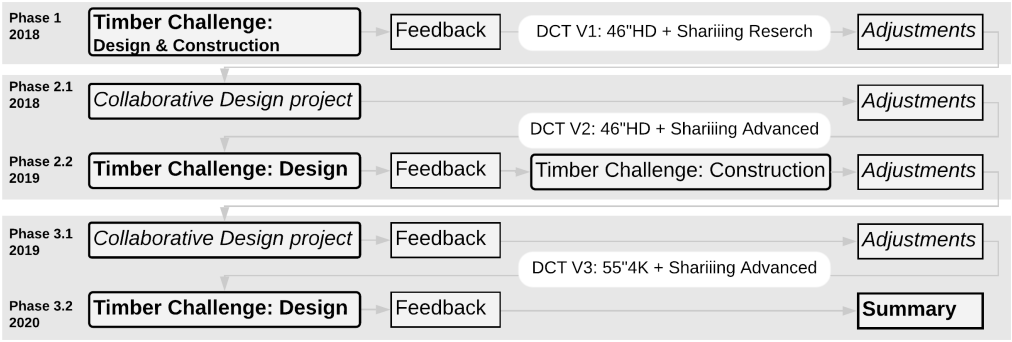
The "Architecture, Timber, Construction" postgraduate program curriculum at ENSTIB (Engineering School of Wood Technologies and Industry) offered a context to the experiment. The students have either architecture, timber or civil engineering background. During the first semester, they work in teams on a Collaborative design project and go to other curriculum classes. During the second semester, they also work in teams, but on Timber Challenge (original French "Défis du Bois"[2]), and follow an internship at architecture or engineering firm.

The subject of a Collaborative design project is usually a housing as the main program with some public buildings in addition. Every student team must design a project in detail, starting with an architecture design, which is further supported by engineering solutions and calculations. The project lifecycle and economic aspects are also in the scope.

Timber Challenge exercise is a project-based learning opportunity (Dunkin, 2000), which is given to 10 student multidisciplinary teams to first design and then construct a wooden microarchitecture project in collaboration. Such an exercise gives a realistic scale to the projects. It strongly encourages students to foresee and avoid problems related to their design choices (Kubiatko and Vaculová, 2018), and also pushes students to anticipate construction solutions adapted to their designs and curriculum-related skills.

Presented aspects of these pedagogical exercises shape a favorable context for our observations of collaboration and of collective decision-making with the DCT (Bolshakova et al., 2019). The teams used a digital collaboration tool (a multi-user touch table) with Natural User Interface at weekly project review meetings: digital collaboration sessions.

Figure 1
Schema of the digital collaboration experiment steps




### *Main phases of the experiment*

The research was carried out in three main phases over a three year period ( Figure 1), during each phase the student teams were working with a pedagogical team with DCT. Specifically, in Phase 1, the Step 1 was the Timber Challenge design and construction phases, Step 2 was the collection of the users' feedback and the adjustments to the collaboration sessions. Phase 1's feedback showed the utility of DCT and suggested improvements for the next phase.

In Phase 2.1, as in Step 1, the students were introduced to the work with the DCT in the first semester during the Collaborative design project. The introduction aim was to train all the students to be efficient with the digital collaboration tool during the upcoming Timber Challenge. The next Phase 2.2 started with Step 1 - the Timber Challenge 2019 design phase and feedback collection. It then concluded with Step 2 Timber Challenge 2019 construction and the new adjustments. Phase 3 also had 2 parts, and was strongly based on Phase 2, and it concluded the experiment. In this paper we focus on the DCT use feedback from Phase 3 to complete the knowledge and on pedagogical feedback.

### *Digital collaboration table short overview*

The DCT in the experiment context was used for co-located synchronous collaboration with a focus on visualization and annotations through NUI interactions for decision-making. The design documents modifications and distant collaboration are not in the scope of the study, even though Shariiing provides a function of connection to another distant Shariiing.

The DCT's configuration, has evolved through the experiment due to software and touch technology improvements, and also as an answer to the users (professors and students) needs. The evolution can be distinguished through the versions of DCT: V1, V2 and V3 (see Figure 2, Figure 3, Figure 4). Figure 1 illustrates the moments of version implementation during the experiment. The main difference was in: 1.The software versions: V1 - "Shariiing Research", V2,3 - "Shariiing Advanced"; 2. Screen size and resolution; 3. Touch technology: V1 - infra-red, V2,3 - projected capacitive (see Figure 1). However, the essence of the DCT stayed the same.

Before the session students prepare the relevant documents. They either stock them (2D documents, videos, web-pages) into the cloud which is connected to the DCT, ether they share with the DCT a screen of a laptop through a Shariiing connection client if they want to visualize and manipulate a BIM model (see Figure 5).

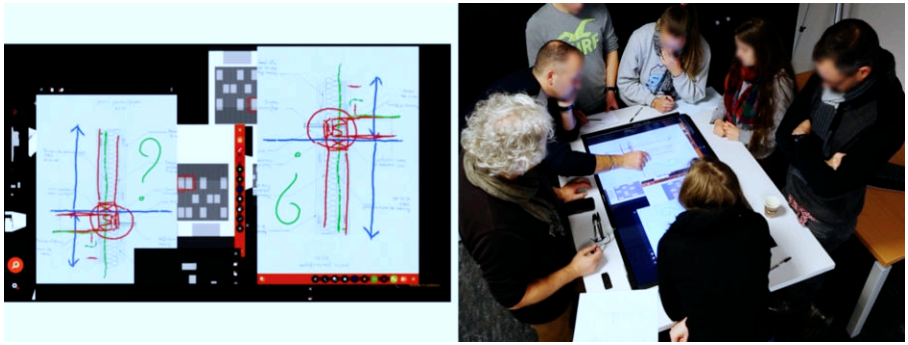


Figure 2
Collaboration with DCT V1: annotation of façade detail

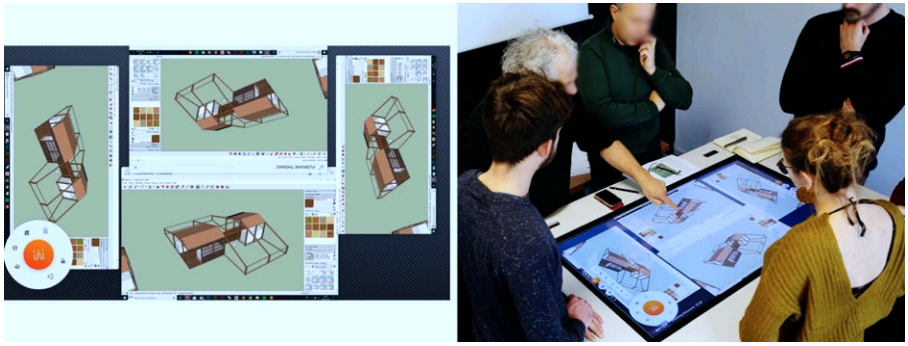


Figure 3
Collaboration with DCT V2: interactions with 3D model shared from SketchUp

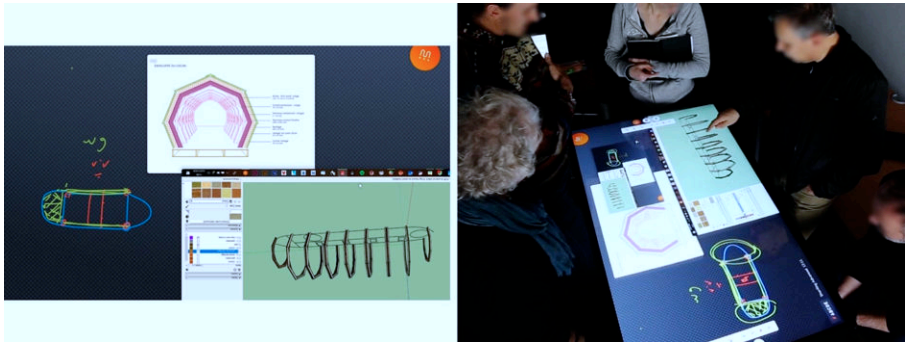


Figure 4
Collaboration with DCT V3: 2D section and 3D model visualization, background sketching

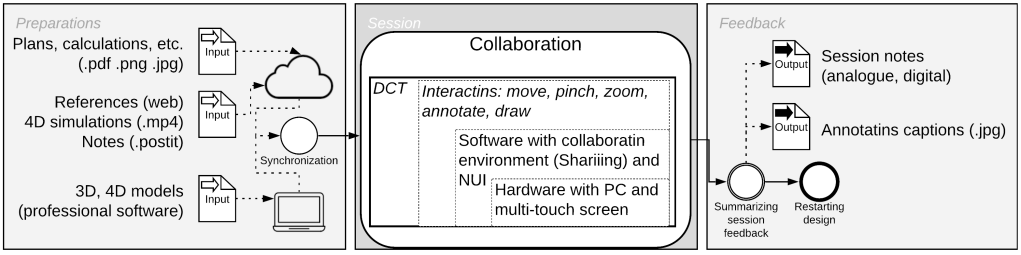



Figure 5
Schema of the process of synchronization of the documents for the session and session feedback outputs

Thus, when using Shariiing Advanced (the latest version of the Shariiing software), it is possible to share a view from a BIM viewer or design software (e.g., Archicad, Cardwork, Navisworks, etc.) directly into the Shariiing collaboration environment, and to keep the natural interactions and simple annotations, or manipulate the model from the computer used for the view sharing.

In the current configuration, users may only save an annotation (Figure 3) on a project document as a new 2D image - the annotation capture (a screenshot) or draw a quick sketch (Figure 5). Even though such limitations do not ease design modifications, they yet offer to users the tools for a focus on discussion and decisions.

### *Digital collaboration sessions participants and used documents*

The digital collaboration sessions (DCS) were dedicated to the students project progress review and advising. Therefore, in correlation with the project progress, the potential number of DCS was different.

During the more exploratory Phase 1 only 9 users participated at DCS, where 3 users were the members of the pedagogical team and the other 6 were students (2 teams of 3 students) of the "Architecture, Timber, Construction" program. Further, all the program students (in 10 teams of 3/4) were participating: 30 on phase 2, 31 on phase 3.

The professors were the constant members of the curriculum pedagogical team, so they were the same 5 users at Phases 2,3.

Most of the students were already active users of 3D modelling tools, more than 60% of them are using the tools often or all the time. Almost a fifth of the total number of students were familiar with 4D before joining the curriculum. For example, at Phase 3 more than a quarter of students were familiar with 4D.

Students were preparing plans, sections, details, 3D models, 4D simulations and other documents comprising their projects. Most of the sessions without 3D models were based on 2D documents, however, once the project advanced and the 3D of the project was on the table it became a center of discussion. Table 1 summarizes the number of those present at DCS teams and the documents they used.

## RESEARCH AIMS AND TOOLS

### *Research scope*

In order to design a collaboration support tool with a well-adapted interface to AEC users, we study the use of DCT by the experiment participants. Certainly, the collaboration workflow corresponds to the project type and project development phase.

Our study focuses on the synchronous collocated collaboration (e.g. meeting) of a project team with DCT. With this paper we cover the following aims of the experiment:

- Evaluate the users' perception of utility and usability of the digital collaboration table and emphasize the advantages and current limits of such a tool;

- Emphasize the lessons learnt from the implementation of the DCT into the pedagogical context.

Also, with DCS observations, we aimed to better portray decision-making and main collaboration dynamics aspects, such as: duration of the session, documents used for discussion, interaction gestures, and decision-making points. Which are in the scope of the study but not of this paper.

### *Data collection tools*

The users' feedback was collected through an extensive questionnaire filled out by the users and through the semi-guided interviews with student and pedagogical teams.

The questionnaire was comprised of multiple parts to collect information on different subjects (System Usability Score, Team Reflexivity, Technology acceptance, open answer questions and study of 4D BIM uses perception).

To complete users' feedback on the digital collaboration experience and the table, as well as on their team collaboration experience, a series of semi-guided interviews was conducted at the end of the pedagogical exercises. Every student team and the pedagogical team shared their team experience at a recorded interview. The group interview was chosen over an individual one to highlight the team collaboration experience.

Also, the observations of DCS and of users' interactions were assisted with video recordings. The observations and interview results reveal the utility and collate suggestions for improvements to the support, as well as identify the digital document types used for different session activities, covered in a previously published work (see (Bolshakova et al., 2019).

This paper focuses on the correlation with the System Usability Scale (SUS) scores (Brooke, 1996) and qualitative feedback results from the analysis of interviews (Braun and Clarke, 2006). The pedagogical team presents their feedback on the advantages of DCS.

## USABILITY FEEDBACK SUMMARY

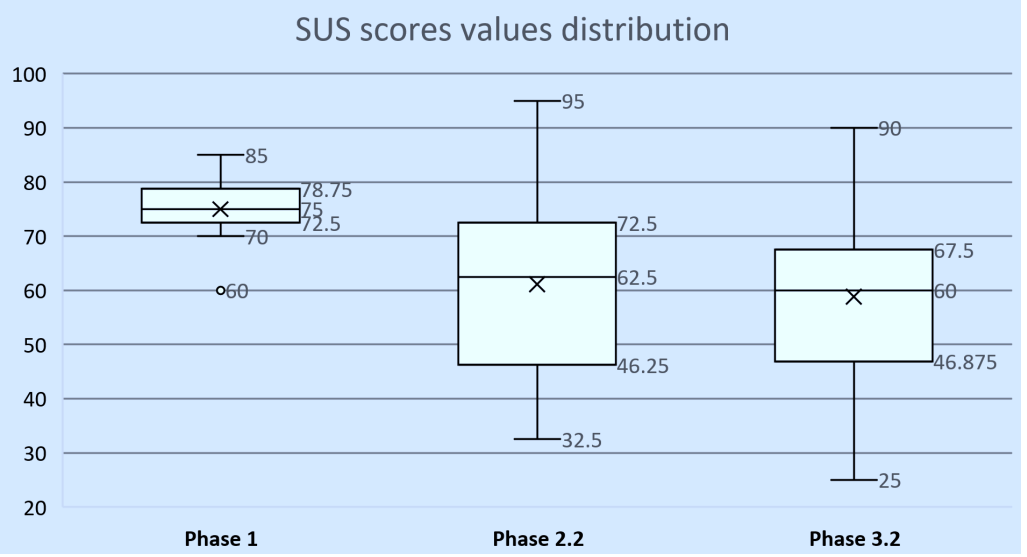
### *SUS scores summary*

Due to the mixed approach to DCT evaluation by users, the results revealed a variety of user experience aspects with DCT and collaboration. The SUS mean scores from all the user categories together (professors, students: architecture, timber engineering, civil engineering) were 75 for Phase 1, 61 for Phase 2.2, and 60 for Phase 3.2. The methodology of the SUS scores (Brooke, 1996) recommends we interpret these scores as: 75 "Good", 61 "OK", and 60 "OK"; according to a scale from 0 to 100 (percentiles), with a passing range starting from 68 (Brooke, 1996). Figure 6 summarizes the scores.

| Phase | Pedagogical exercise | DCS number | Student teams at DCS | Participants | | Teams using | |
|---|---|---|---|---|---|---|---|
| | | | | *students* | *professors* | *3D* | *4D* |
| **Phase 1 2018** | Timber Challenge | 3 | 2 | 3 | 2/3 | 2 | 1* |
| **Phase 2.2 2019** | Timber Challenge | 4 | 10 | 3 | 2/3 | 10 | 5 |
| **Phase 3.2 2020** | Timber Challenge | 2 | 10 | 3 | 2 or 3 | 9 | 0 |

Table 1
Summary of DCS teams and documents

Figure 6
SUS scores values for Timber Challenges for all users together




However, these numbers should be reviewed in detail. For example, the score from Phase 1 is higher, due to the general user profile being "innovation eager and curious about technology". The next two phases' scores suggest a larger variety of users' opinions on the DCT.

Also, SUS scores from the user categories are different; the professors mean is 80, thus suggesting that DCT is "Good" and close to "Excellent", on the other hand the students mean is 60. Even with the score appearing low, more than 80 % of users confirmed that: in general, with the DCT they could perform their actions well (with no obstacles) during collaboration sessions. The score from those users is 67, which is suggests a score rather close to good. Therefore there is a need for an analysis of general acceptance of technology and qualitative feedback.

In addition, the analysis presents a pattern between the number of a user's years of experience and the score. The users with more than 2 years of experience tend to give higher scores, moreover the active and experienced users of 3D modeling score similarly. Furthermore, the analysis previously showed higher scores from the architects and lower scores from the civil engineers, but the last phase of the experiment did not reveal a particular difference among the scores of those different user backgrounds. However, the study highlighted again that the DCT is most useful to the users with a strong connection to CAD and BIM, and it is also most useful to those who already have several years of experience, as they give better scores.

The future comparison of the SUS scores from the student teams (instead of single users) to both team performance and team collaboration culture would give a better understanding of the DCT's perceived usefulness on the group level. It will portray a collaboration group persona through the team reflexivity and activities analyses. The complex analysis will give directions of improvement teaching multidisciplinary collaboration and contribute to the collaboration tool design.

### *Team collaboration and DCT use*

In addition to the quantitative data, the qualitative data from the student teams gives rather positive feedback. The students state the interactivity and visualization quality as the most interesting aspects of the DCT. They also mention the general "playful curiosity" and "nivelate the student-teacher barrier" aspects as the new experience from the project review meetings.

However, a half of the teams claims that they did not feel fully confident about their use of DCT, even after the first semester introduction and active use of the DCT. The main reason, highlighted during the interviews was "stress and pressure" from the dense rhythm of the DCS and need to collaborate with the other disciplines. The teams with a strong collaboration were producing better designs, therefore felt confident at the DCS and used DCT for their benefit.

## PEDAGOGICAL TEAM REFLECTION ON THE EXPERIMENTS

The primary initiator for the experience with the DCT was the pedagogical team. As they have done in the past, the focus was on the student projects rather than the optimization of the DCT use. Because of this, the team was available to provide feedback on DCT usability just as the students were. In addition to the DCT users' feedback, the professors emphasized the pedagogical point of view on DCT implementation into teaching design and construction to multidisciplinary teams. Besides, they have provided reflections on the changes the DCT brings to the design process, the DCT advantages, disadvantages and reflections on future goals.

### *Augmented participation and interactions*

Since all the users are united around the DCT and are disposing the same project documents, so there is a certain clarity of visualization and democratic natural user interface interactions. The pedagogical team has access and a clear scope of the project state. Before coming to the session to see the professors, first, the students have to cease work on their design processes, then they take time to emphasize the progress and prepare the session documents, and finally students do not stay in front of their computer and are expected to participate at the decision-making.

### *More efficient feedback but lack of emphasis*

Due to the better access to the documents and interactivity, the pedagogical team provides better and more thorough feedback on the students' projects. However the current DCT configuration and the collaboration approach did not offer a hierarchized list of session decisions, nor did it offer easy planning for further development and tasks assignment. Therefore, most of the student teams leave the session with a great deal of unstructured feedback they would not naturally implement efficient collaboration practices. The pedagogical team highlights the need for a change, first, of the session scenario, by adding a few minutes to summarize the decisions and plan the future session with the tools already integrated into the DCT, and second, to provide hands-on experience to students in multidisciplinary collaboration practices and tools.

### *Design with 3D and multidisciplinary teams*

The pedagogical team agrees on one of the main advantages of the DCT, it is the ease of visualization and interactions with 3D and 4D models. Yet, not all the members of the curriculum's multidisciplinary teams are familiar with 3D modeling, therefore the 2D documents are still the core of the early design process.

The 2D provides better communication within the team, gives every member an equal ease of contribution. The DCT provides an interactive aspect to the 2D documents as well, and for now they are used even more often than 3D as a support during discussion, especially in the early stages. However, the pedagogical team has noticed that even a single 3D model for the Timber challenge provides enough information about the project.

The DCT, as a medium of collaboration, fosters new ways of working together, therefore it forces a change of habit for the design practices and need to adapt for the digital collaboration session workflows. The future pedagogical strategy must focus on the development of the digital collaboration culture in the multidisciplinary student teams. So the students would be able to form reflexive efficient teams and adapt to multidisciplinary workflow.

## CONCLUSIONS

With this study, we continue to explore the three years of pedagogical experiment feedback gathered through observations, questioners and interties analysis. The experiment context offered an opportunity to implement a digital collaboration tool for the project review sessions and observe the use of such a tool by multidisciplinary teams.

From the researchers' perspective, the experiment summary contributes to the user-centered design approach of a new collaborative decision-making tool. From the pedagogical perspective, it concludes the pedagogical team reflection on the use of a digital tool and teaching strategies for collaboration.

This paper focus on the System Usability Scale (SUS) scores revealed a correlation between users' appreciation of the digital collaboration table and their years of experience in professional and with CAD and 3D modeling. Also, the feedback from students and professors highlights the need to focus on the reinforcement of collaboration culture inside the team, so the teams would fully benefit from the digital collaboration tool. Implementing and experimenting with the collaboration tools during the academic curriculum prepares future professionals for future multidisciplinary collaboration in the industry.

## ACKNOWLEDGEMENTS

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