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PhD thesis by Mads Brath Jensen

AALBORG UNIVERSITY

DEPARTMENT OF ARCHITECTURE, DESIGN AND MEDIA TECHNOLOGY

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PhD thesis by Mads Brath Jensen

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iii. Summary (eng.)

This PhD thesis examines interactive and collaborative design methods for robotic fabrication in architecture. Through the study of design thinking, computational design exploration, robotic architecture and material systems, the thesis proposes a design framework for co-creative human-material-robot processes in architecture. This integrated design framework seeks to bridge a gap in current processes of digital fabrication, where designers shift from being highly engaged during design processes, to designated passive bystanders during ongoing fabrication processes.

It is believed that robotic fabrication, supported by cyber-physical frameworks for interactive and collaborative processes of human-material-robot making, can support and enhance the creative exploration of design modelling and design making in architecture. To investigate this hypothesis, the thesis asks how interactive and collaborative robotic fabrication can contribute to creative 'co-evolutionary' design process in architecture and how such creative activities will influence cognitive design processes.

Focusing on the methodology of Research-through-Design the work presented in this thesis advocates for design research being performed through experimental work, involving digital models, physical prototypes, and full-scale demonstrators. The project comprises a sequence of five discrete experimental studies that progressively alternates between author-driven and student-driven design processes. This strategy allows for an alternation between subjective and objective registrations of the robot-based design processes and an uncovering of the potential impact and relevance of diverse levels of design experience.

Based on the findings of the thesis, the proposed design methods were found to progressively enhance interaction with the robotic fabrication process. The opportunity to directly interact with a robotic arm and suggest changes during the ongoing fabrication process allowed for initiation of fabrication processes that were not entirely determined, thereby substantiating trial-and-error based design explorations that allow for reflection-in-action to occur.

The thesis also concludes that if decision-making is to be shared between all agents in a co-creative human-robot design framework, the robotic framework must incorporate strategies for machine learning and artificial intelligence.

iv. Resume (da.)

Denne PhD-afhandling undersøger interaktive og samarbejdende designmetoder for robotbaseret fabrikation inden for arkitektur. Gennem en undersøgelse af designtænkning, computerdrevet designudforskning, robotbaseret arkitektur og materialesystemer foreslår afhandlingen et designsystem til samskabende menneske-materiale-robot processer inden for arkitektur. Dette integrerede designsystem søger at lukke et hul i de nuværende digitale fabrikationsprocesser, hvor designere skifter fra at være dybt engagerede under designprocessen til at være passive tilskuere under igangværende fabrikationsprocesser.

Det forventes at robotfabrikation, understøttet af virtuelle-fysiske systemer til interaktive og samarbejdende menneske-materiale-robot fremstillingsprocesser, kan understøtte og forstærke den kreative udforskning af designmodellering og designfremstilling inden for arkitektur. For at undersøge denne hypotese spørger afhandlingen, hvordan en interaktiv og samarbejdende robotfabrikation kan bidrage til kreative samudviklende designprocesser inden for arkitektur, og hvordan sådanne kreative aktiviteter vil influere kognitive designprocesser.

Med fokus på metoden for ’forskning gennem design’ advokerer det præsenterede arbejde i denne afhandling for, at designforskning udføres igennem eksperimentelt arbejde, hvilket involverer digitale modeller, fysiske prototyper og fuldskala demonstratorer. Projektet indeholder en serie af fem individuelle eksperimentelle studier, der progressivt skifter mellem designprocesser drevet af henholdsvis forfatteren og studerende. Denne strategi tillader en vekslen mellem subjektive og objektive registreringer af den robotbaserede designproces samt afdækning af den potentielle indflydelse og relevans af forskellige niveauer af designerfaring.

Baseret på afhandlingens resultater kan det identificeres, at den foreslåede designmetode gradvist forstærkede interaktionen med den robotbaserede fabrikationsproces. Muligheden for at interagere direkte med en robotarm og forelå ændringer under den igangværende fabrikationsproces tillod igangsætning af fabrikationsprocesser, der ikke var fuldt fastlagte. Derved understøttes designudforskning baseret på trial-and-error, hvilket muliggør reflection-in-action.

Afhandlingen konkluderer også, at hvis beslutningstagning skal være delt imellem alle deltagere i et kreativt menneske-robot designsystem, skal robotsystemet inkorporere strategier for maskinlæring og kunstig intelligens.

v. Acknowledgements

After more than three years of research, I can finally write this note of thanks as the finishing touch on my dissertation. It's been a fantastic journey of learning and creative exploration, and many wonderful people have assisted me throughout this research endeavour. First of all, I would like to express my gratitude to my two thesis supervisors.

Professor Hans Jørgen Andersen, Head of the Department of Architecture, Design and Media Technology at Aalborg University, generously offered me a fully financed PhD stipend and allowed me the freedom to pursue my research interest. Throughout the project, I've profited from his research experience, and I'd like to thank him for his confidence and encouragement.

Isak Worre Foged, Associate Professor at the Department of Architecture, Design and Media Technology at Aalborg University, is the primary catalyst behind the more significant part of my research endeavour. In the last decade, Isak has been my colleague in both teaching and research activities. Still, most important, Isak is a dear friend to whom I owe a debt of gratitude for nudging me down this research path and passionately guiding me along it.

Without my colleagues at CREATE, it would not have been possible to complete this PhD dissertation. I would like to thank Poul Lund, Peter Skotte and Jens Munk for all their assistance in creating custom fixtures, printing and welding unique robot parts and for sharing their material know-how. Thank you to Avishek Das for his huge engagement and support with robotic fabrication and visual analysis. Thank you to Vasiliki Fragkia for her assistance in the assembly of physical demonstrators, and to Michael Hansson for his help in establishing an interactive robotic framework. At CREATE, I've been surrounded by helpful colleagues, and I'd like to thank all of them for having helped me with the many small challenges you face during a PhD project.

Several students have assisted me during the many hours of robotic fabrication. I would especially like to thank Gerd Kay Markvard and Mikkel Esrup Steenberg for their commitment during the concrete printing process. I would also like to thank all the students participating in the TSE course module at the 2nd semester MSc in Architectural Design in 2018 and 2019. Without your willingness to explore robotic design processes together with me, I could not have made the discoveries I did.

During my PhD thesis, I was fortunate to be invited to a 3-month research visit in Linz, Austria, by Univ.-Prof. Johannes Braumann. I'm grateful for having had that opportunity, and I would like to thank Johannes for his great hospitality and the research assistance he offered during my stay.

None of this would have been possible without the loving support of my parents and my brother. They have always believed in my projects, even though they do not always fully understand them. But yes, it's got something to do with robots!

And last but not least, to Susanne, my girl, for always preserving a loving and robot-free space.

vi. List of contents

1.

Introduction

1.1 Motivation

The process of making

The process of making has always fascinated me. The creative process of exploring solutions to a challenging problem through the creation of physical prototypes is for me, one of the most rewarding aspects of a design process. What starts as a collection of abstract ideas, only limited by imagination, evolves into tangible solutions which can be further explored through suitable processes of physical making, unveiling their potential to act in the physical environment. In the perfect scenario, the physical processes of making are inseparable from the cognitive processes of idea generation - the two types of processes iteratively inform and improve each other.

In more than a decade, I've been fortunate to participate in both teaching and research activities that explore the potentials of, and relations between, computational design processes and computational making activities. In this context, creative design processes have been explored through the development of computational systems focused on generative design approaches and the making of material objects through digital fabrication technologies. Common for almost all these design explorations are their process-oriented approach and their focus on creating and investigating computational design systems that establish relationships between environmental performance, material properties, spatial sensations, assembly methods, and fabrication processes.

This compilation of teaching courses and research projects constitutes a range of diverse computational systems each investigating methods for the integration of form generation and digital fabrication. Common to all these investigations is the fabrication and assembly of 1:1 demonstrators – a build artefact acting as an embodiment of the *instrument of inquiry* (Dalsgaard, 2017). Although these investigations resulted in critical explorations of computational design methods and challenged the potential of integrating digital fabrication technologies, they never fully succeeded to integrate digital fabrication within the explorative design process. The design methods only supported a type of design process best defined as fabrication-informed design exploration. In these design processes, information concerning fabrication (such as machine dimensions, speed, cutting depth, material sizes) is utilised as design constraints and as input for the generation of machine-specific fabrication files. But, although these digital fabrication methods allow for an active engagement with physical objects and their materiality, they exclude the designer during the fabrication process. This division is observed in current approaches of running automated processes, where making machines are executing predetermined commands that fabricates a predefined form – excluding uncertainty, exploration and the opportunity for creative input, rendering the designer superfluous.

I strongly believe that there is a great potential in facilitating digital fabrication processes, in which the architect – the human element - can actively engage in the creative process of making.

Tools and technologies

> *"It is impossible to stress to much the difference between bare hands and armed hands… The hand equipped with a good tool renders the hand equipped with a poor one ridiculous." (Bachelard, 2002)*

My first engagement with digital fabrication, involving both the creative exploration of potential digital-driven solutions and their subsequent materialisation and assembly into physical prototypes or demonstrators, was defined and restricted by the tools and technologies offered by current modelling environments. In my case, dependency on tools and interfaces by leading software providers challenged the preparation of my master theses in 2008. At that time, recent developments provided users with plug-ins and scripting environments that exposed the inner workings of the software, allowing for the construction of custom scripts that surpass the limitation of available tools and standard procedures. The work conducted during my master thesis utilised RhinoScript, a scripting tool for the 3D modelling environment Rhino 3D, to develop and explore a computational framework that generates an environmentally and structurally informed frame+membrane system (Jensen *et al.*, 2009; Jensen, Kirkegaard and Holst, 2010). This project allowed for an exploration of not only potential design solutions but also of the computational processes and the negotiation between the various driving forces at play – a design exploration that was made possible through the construction of bespoke computational tools. To me, this marked the transition from only using tools, to also making tools.

1.1.1. Computational Design in Architecture

As emphasised in the previous quote by the French philosopher Gaston Bachelard, the process of making is intrinsically tied to the possibilities and limitations of available tools. Seeking to equip the designer with better tools, leading modelling software providers have made great effort to develop interfaces and accessibility to their programming libraries and languages. These alternative approaches to design software were also called for by researchers in the field of digital design. As an example, Axel Kilian, PhD in Design and Computation, suggested that: "*software should evolve around the design task, not the other way around*" and that *"this is already happening in the academic environment with students developing their project specific tools from a platform of core software and languages*" (Kilian, 2006).

Today, current modelling software now supports the development of bespoke computational design tools that take advantage of access to extensive programming libraries and provide more intuitive and designer-friendly interfaces that allow for visual programming, text-based programming, geometric representation, or often a combination of these. The introduction of parametric design software, such as Generative Components (by Bentley), Grasshopper (for Rhino), or Dynamo (by Autodesk), has had a pronounced influence on design thinking (Oxman, 2008). Although there are still cognitive issues involved with the use of parametric design software (Aish and Hanna, 2017), it has allowed architects to escape the limitations of software applications and explore novel design solutions through programming and execution of algorithms (Tedeschi, 2014).

In understanding the potentials of computational design tools for the exploration of creative solutions, it is essential to appreciate how this modality differs from the preceding design modes in architecture, such as analogue drawings, digital CAD drawing, and the use physical models. For centuries, the act of drawing has been the preferred medium for expressing, organising, and exchanging ideas, as well as a means for predicting design outcomes. Drawing, as a design activity, is a natural and manual gesture that establish a direct link between ideas and the signs created to represent them. This additive process, while allowing for a great range of (in)determinacy and (im)precision, is incapable of managing the forces and constraints of the real world, leaving all associative relations to be managed through the cognitive capabilities of the designer (Tedeschi, 2014). The introduction of CAD software digitalised the freehand drawings, added the possibility of defining geometric primitives, and allowed for atomisation of repetitive task. However, with CAD software, the designer is still interacting directly with the design object, although now through a mouse, and still basing design outputs on additive processes without correlation between forces and forms. Introduced by pioneers like Antoni Gaudi, Heinz Isler, and Frei Otto, the use of physical models represents an approach towards structural optimisation through investigations of materials, shapes, structures, and their associative relations (ibid.). Based on form-finding strategies this approach allows for design processes that embrace the dynamic forces absent in the other two modalities and thereby shift the process of exploration, from primarily involving cognitive processes externalised through drawings (analogue or digital), to cognitive processes informed through interaction with dynamic and self-optimising physical models. The use of physical models is often driven by a single force, gravity, and although this approach enables an exploration of novel structures it simultaneously marks a trajectory from simple systems towards more complex systems negotiating with a series of interrelated and interacting sub-systems (Menges and Ahlquist, 2011). It is towards this negotiation between interacting elements that the potential of computational tools differs from the other design modalities. In dealing with environments and design tasks that embrace several forces and constraints, computation has the potential of providing a framework for negotiating and interacting with heterogeneous data. Taking advantage of algorithmic procedures and parametric dependencies (through the type of software mentioned earlier) the implementation of computational tools has allowed architects and designers to engage with architecture as a system, instead of as an object, enabling interaction with design processes instead of single objects. A similar shift of orientation in architecture has been put forward by David Leatherbarrow regarding the discussion of architectural performance, in which he argues for a shift from what architecture *is*, to what it *does* (Leatherbarrow, 2005).

In examining the impact of computation on the perception and realisation of architectural solutions, computational design researcher Sean Ahlquist and Professor of computational design Achim Menges defined the computational design approach as "*one which focuses on the execution of variational methods for the purposeful intent of resolving the complexities that exist in the interrelation and interdependencies of material structures and dynamic environments*" (Menges and Ahlquist, 2011). The last decade has seen a promising development in modelling software that supports

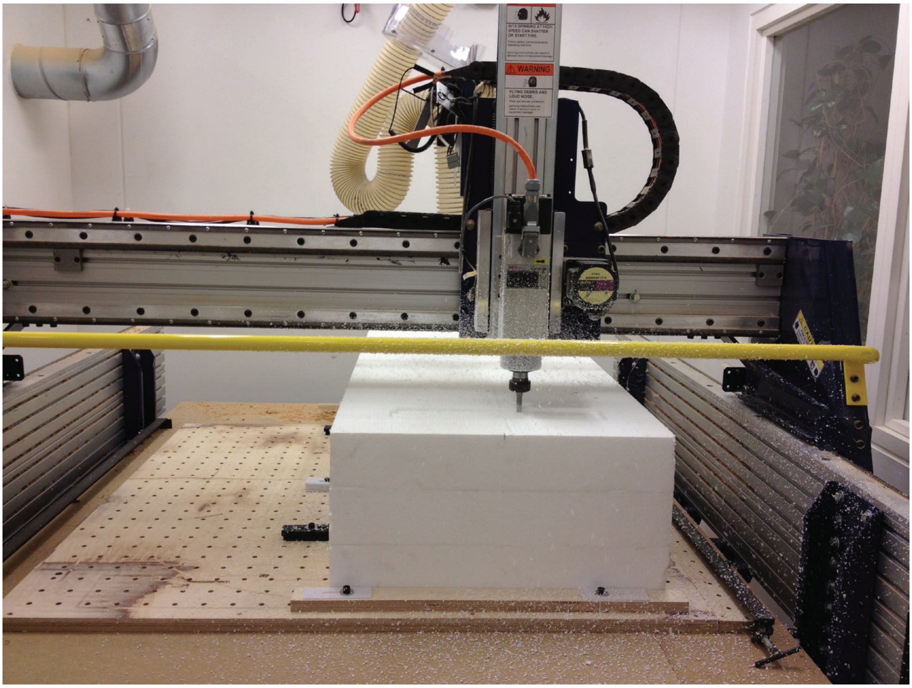


Figure 1.1.
Milling of foam model with a 3-axis CNC milling machine.
Photo by Mads Brath Jensen

the definition and construction of such relationships and interdependencies, taking advantage of the iterative, recursive, and expansive processes of computation (ibid.). It is the potential freedom afforded by the (re)construction of algorithms that drives these expansive computational design processes, allowing the designer to adapt the capabilities of the design system towards the unpredictable nature of design processes. As argued by Professor in Algorithmic Design, Kostas Terzidis, this affects the way we engage with the computer, as these must be "*acknowledged not only as machines for imitating what is understood, but also as vehicles for exploring what is not understood*" (Terzidis, 2006).

Using the computer as a driving force, the development of increasingly sophisticated computational design tools has enabled architects to extend the exploration of geometric solutions, including their intrinsic (ex. structural, material) and extrinsic (ex. environmental, social) performance, to incorporate the making and fabrication of architecture. In the last two decades, the field of digital fabrication has coupled creative form-finding processes with CNC fabrication tools, including technologies as CNC mills (see figure 1.1), laser cutters, vinyl cutters, and 3D printers. By informing the design process with parameters related to materialisation and production, the generation of solutions can take into account the operational constraints of the machines, ensuring realisable outcome, and simultaneously encouraging full exploitation of the operative techniques (Klinger, 2008). The control of fabrication logics allows for easy transferral of information between design system and fabrication machinery, facilitating a vital feedback loop in which the making of prototypes promotes a more diverse range of considerations towards design-to-fabrication processes and supports higher degrees of material sensibility. The following quote by Menges substantiates the importance of, and the potentials in, utilising computational design methods and tools in architecture.

> *"The underlying logic of computation strongly suggests [a design approach], in which the geometric rigor and simulation capability of computational modeling can be deployed to integrate manufacturing constraints, assembly logics and material characteristics in the definition of material and construction systems. Furthermore, the development of versatile analysis tools for structure, thermodynamics, light and acoustics provides for integrating feedback loops of evaluating the system's behaviour in interaction with a simulated environment as generative drivers in the design process. Far beyond the aptitude of representational digital models, which mainly focus on geometry, such computational models describe behavior rather than shape." (Menges, 2008)*

The creative development and use of computational design tools have been crucial to digital fabrication in architecture – interfacing between design and fabrication. Several techniques have been developed to generate, describe, predict, analyse, evaluate, simulate, convert, and manage the explorative design processes, requiring designers to rethink their design processes and the methods they employ.

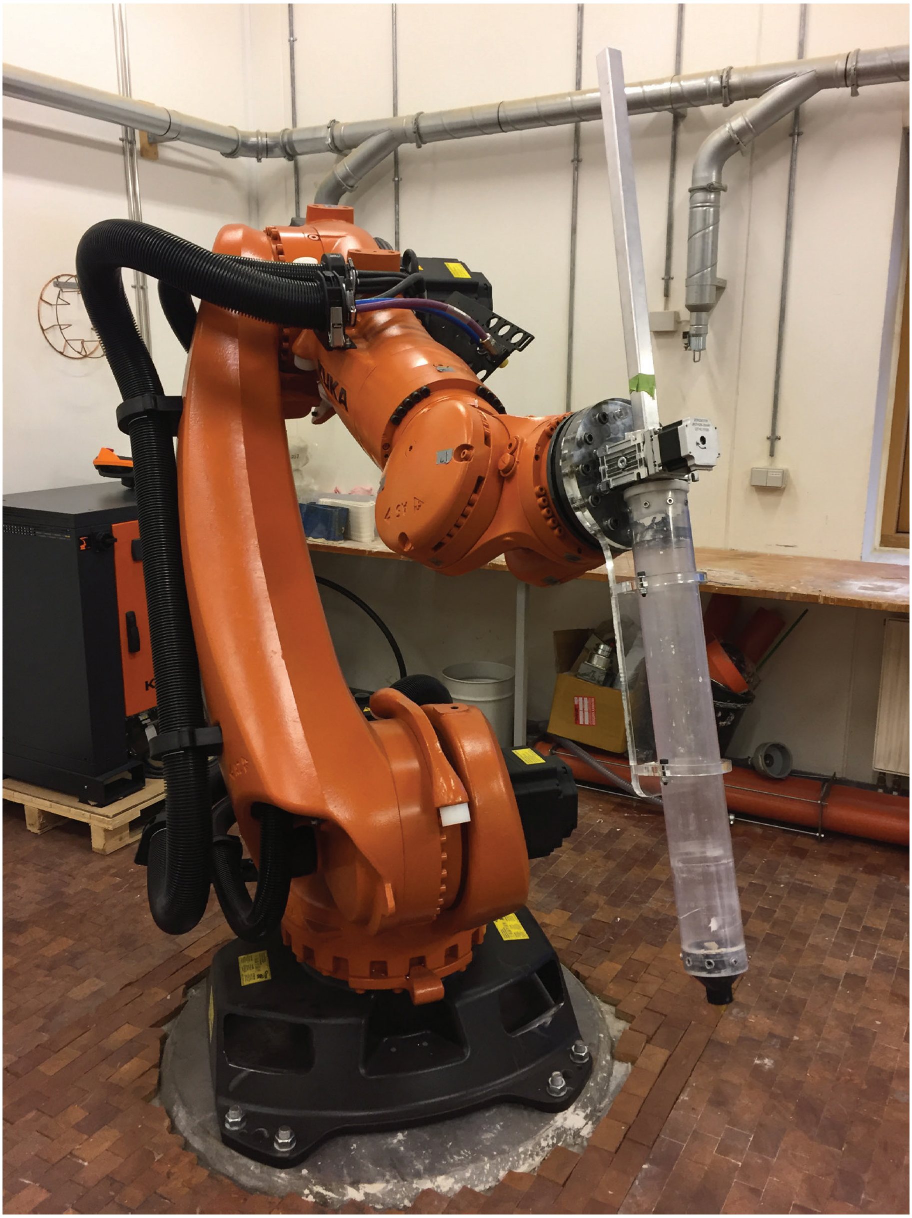


Figure 1.2.
The 6-axis robot arm (KUKA KR300 R2500) installed in the Robot Lab. at the Utzon Center, Aalborg, Denmark. Here mounted with a clay extruding end effector.
Photo by Mads Brath Jensen

Although the development of computational methods has "*facilitated a greater fluidity between design generation, development, and fabrication*" (Dunn, 2012), which allows the designer to interact with the entire process from initial idea to final product, the use of CAM technologies still seems to restraint the range of exploration within fabrication-driven computational design processes. Digital fabrication has shown how fabrication technologies and the inherent constraints of the machinery (such as material type and dimensions, machining areas, and tool limitations) can inform the computational model ensuring that potential design solution exploits the potentials of digital fabrication and that they comply with fabrication constraints. However, the fabrication processes in most industrial CNC machinery are based on specialised techniques performed through fixed tool-sets and restricted movement patterns. The creative and explorative freedom that permeates the computational design processes is therefore often non-existent in the processes of standard CNC fabrication, leaving a procedural gap between the interactive and indeterministic processes of design exploration and the dissociated and deterministic processes of digital fabrication.

During the last decade, a new fabrication technology has infiltrated design studios and architectural research laboratories. A new platform of agile and flexible fabrication robots that allows for questioning and reimagination of the limitations of standardised materials, forms and sizes that propelled the design processes of digital fabrication (Dass and Wit, 2018). The designer now has the opportunity to redefine the computational design processes and design the processes of new material systems and the tools for robotic fabrication.

1.1.2. Robots in Architecture

> *"Digital fabrication and robotic fabrication are two points along technological and chronological continuums… yet one does not replace the other. Robotic production builds off digital fabrication technologies and provides degrees of freedom that open up new avenues of making." (Dass and Wit, 2018)*

Unlike industrial CNC machinery and the more common off-the-shelf 3D printers and CNC routers, industrial robotic arms, as the one shown in figure 1.2, are not specialised towards the completion of certain tasks and not nearly as accurate or powerful. When acquiring a brand new, top-of-the-line robot arm one only gets the 'naked' arm, no hand and no tool. With the robot arm, however, one gets the freedom to mount whatever tool or end effector, be it a high-end CNC spindle for milling purposes or a self-made custom tool (digital or analogue) with the capability of solving a particular task. The simple process of attaching a new tool to the robot arm and its ability to move and orient to a given location in real space makes robotic fabrication "*significantly more flexible than fabrication using traditional CNC machines*" (Nicholas, 2018). Although universal and multifunctional, they can be turned into highly specialised machines that can execute "*multiple and varied tasks to create unique and carefully crafted objects*" (Edgar, 2008).

Figure 1.3.
The robotic fabricated brick facade of the Gantenbeim Winery, 2006, Switzerland.
Project by Bearth & Deplazes Architekten and Gramazio & Kohler. Photo by Ralph Feiner.

In more than a decade, architects and design researchers have explored the potentials of robots and their capacity to engage in a broad spectrum of applications. The first pioneering projects by Fabio Gramazio and Mathias Kohler at ETH Zurich explored robotic placement of individual bricks showcasing the potential of adding digital intelligence to traditional building culture through control and customisation of the robotic fabrication process (Gramazio, Kohler and Willmann, 2014). The control, precision and variant achievable through robotic brick laying is especially apparent in the Winey Gantenbein project from 2006 by Gramaizo & Kohler (see figure 1.3)

Breaking away from traditional fabrication methods, researchers at ICD/ITKE Institutes at the University of Stuttgart, led by Achim Menges and Jan Knippers, has explored various methods of robotic fabrication trough the design, fabrication and assembly of annual research pavilions. This research strategy has been repeated every year since 2010. As an example, The ICD/ITKE Research Pavilion of 2014/15 used robotic fabrication to delicately apply strings of carbon fibre reinforced polymer to the inner surface of an inflated skin, building up the pavilion layer by layer. This specific research pavilion also showcased the potential of adaptive robotic processes through the implementation of real-time force sensors, allowing for correct pressure between the robot end-effector and the flexible skin (Doerstelmann *et al.*, 2015).

Other inspiring projects have explored various methods of robotic fabrication includes robotic rod bending (Macdowell and Tomova, 2011), robotic wire cutting (Pigram and Mcgee, 2011), robotic sheet forming (Nicholas *et al.*, 2015), robotic spatial printing (Retsin, Garcia and Soler, 2018), robotic milling (Brell-Çokcan and Braumann, 2010), robotic weaving (Brugnaro, Vasey and Menges, 2008), robotic carving (Brugnaro and Hanna, 2019), and robotic band-saw cutting, to name just a few fabrication methods.

One of the essential advancements that support investigations in robotic fabrication is the development of parametric robotic control, allowing designers to simulate the movement of robotic arms and generate the robot code needed to physically move the robot along the desired path(s) (Brell-Çokcan and Braumann, 2010). KUKAprc, a parametric robotic simulation/control tools directed towards architects and designers, developed by Johannes Braumann and Sigrid Brell-Cokcan as part of the main goal for the Association for Robots in Architecture (ibid.), has had a vital role in these advancements. By developing KUKAprc as a set of components for Grasshopper, simulation of robotic fabrication can be linked directly with the geometrical changes in the parametric design system, allowing the designer to engage with the fabrication process through very fluid interactions with the virtual robot (Braumann, Stumm and Brell-Çokcan, 2018). With KUKAprc focusing on establishing a connection between Grasshopper (now also available for Dynamo) and robotic arms from the KUKA brand, other initiatives have developed similar software tools for robots from other robot manufacturers, like ABB, Universal Robots, Fanuc, and Denso. With these developments, robotic simulation and control can be embedded within the computational design system, establishing relationships between form generation, structural analysis, environmental simulation, performance evaluation, and robotic fabrication. From the perspective of design exploration, the greatest affordance of these robotic fabrication tools is their capability of changing robotic fabrication from a post-processing activity occurring in the conclusion of the design process, to an integrated process that allows the designer to simultaneously develop, explore, and directly influence all aspects of the creative design process.

As previously mentioned, the integrated design processes of robotic fabrication have not only allowed a continuous exchange of information within the computational design system but also established a relationship between the predicted digital model and the actual physical model through the utilisation of sensor-based feedback systems. These adaptive fabrication processes allow for investigation of design processes that unfold simultaneously with fabrication; processes in which "*the design process is not centered on realising a predefined solution, but instead embraces explorative and experimental processes*" (Brugnaro, Vasey and Menges, 2008). This fusing of design an making processes changes the common file-to-factory approach, in which the design is entirely determined prior to fabrication – a process in which the fabrication is merely a copying of a design (Nicholas, 2018). Instead, these robotic fabrication processes rely on adaptive strategies that afford reciprocity between design models and fabrication (Vasey, Maxwell and Pigram, 2014). With the prospect of adaptive robot arms capable of sensing certain aspects of the physical model, the question put forward by Achim Menges seems increasingly important.

> *"what happens if the production machine no longer remains just the obedient executor of predetermined instructions, but begins to have the capacity to sense, react and act?" (Menges, 2015)*

Several research projects have addressed this question during the last few years. In the previously mentioned ICD/ITKE Research Pavilion of 2014/1, the robot arm is sensing the presence of the inflated skin to readjust the pressure through which it applies the carbon fibre material (Doerstelmann *et al.*, 2015). In the research project "A Bridge Too Far" a robot arm senses the effects of an incremental sheet forming process and adapts to deviations in the final shape by selecting between appropriate corrective actions (Nicholas, 2018). Research into Adaptive Part Variation (APV) has also demonstrated how computer vision sensors can add a feedback loop that enables a robotic arm to detect errors during rod bending, triggering conditional design responses and re-computing the bending parameters for the following rod. The APV strategy thereby ensures the management of any variation (imprecision) in the rod bending process by adapting the geometry of all the affected rods within the spatial rod assembly – facilitating full automation intelligence (Vasey, Maxwell and Pigram, 2014).

These projects, and the research agenda they pursue, are crucial for the advancement of robotic fabrication, but they also, deliberately, keep the human element out of the fabrication process. In all cases, the nature of the material system and the investigated fabrication process makes human intervention impossible, or at least undesirable. The question is, referring back to the initial motivation if similar projects exploring robotic fabrication could benefit from an integration of human interaction, or even collaboration? Instead of designating the designer as a mere bystander passively observing the on-going fabrication process, these processes might benefit from incorporating and adapting to human interaction?

1.1.3. Creativity, Exploration and Intention

If one looks back at the architectural design process and compares the established design modalities, it is apparent that computational design and robotic fabrication has changed and extended the creative process by allowing for an exploration of cyber-physical systems. Based on the brief overview given above, it is evident that the field of robotic architecture is a breeding ground for technological advancements and growing material sensitivity. But the showcased projects also features very complex design systems in which negotiating between several complex processes, both computational and physical, takes place. The form of creativity occurring within these robotic fabrication processes seems to be of another character than the one taking place during hand sketching or manual building of physical models and prototypes - both modalities allowing for dynamic “what-if” conjecturing. Especially during the early phases of the creative design process, the option of pursuing various conjectures is a vital aspect. To critically investigate how robotic fabrication might support the creative processes of early design exploration, it is essential to not only clarify the technological implications but also to understand the cognitive aspect of creativity. In addition to uncovering what creativity is, identification of how to extend this creativity into design thinking is critical for the proposal of suitable robotic-based design methods.

Turning to the field of cognitive science, Research Professor Margaret A. Boden seeks to uncover the nature of human creativity by drawing on examples from artist and scientist, as well as computing models from the field of artificial intelligence (Boden, 2004). Boden’s identification of two different senses of creativity, as well as three forms of creativity, allows for critical insight into the cognitive processes occurring during creative moments. Boden’s work thereby helps to clarify the type of creativity that could potentially be supported through the proposal of robot-based design methods and how one might address the evaluation and possible segregation of creative design processes.

When engaging in any type of creative work, be it painting, handcrafting, gardening, or cooking, a particular sensation of losing time and place might occur. This very positive experience can be characterised by high levels of intrinsic motivation, most evident when engaging in challenging activities. This subjective phenomenon was investigated by Professor of Psychology and Management Mihaly Csikszentmihalyi, labelling it a ‘flow’ experience. Flow research, pursued throughout the 1980s and 1990s, was developed into a clear concept with a well-defined set of conditions and characteristics. The concept of flow went through several iterations ending up being defined as ”*the balance of challenges and skills when both are above average levels for the individual*” (Nakamura and Csikszentmihalyi, 2005). The concept of flow can thereby be understood as a specific balance between action opportunities (challenges) and action capabilities (skills). Through a strengthened focus on this balance, flow experience could be deployed as both a guiding principle for the development of robot-based design methods and as a benchmark for evaluating the resulting design processes.

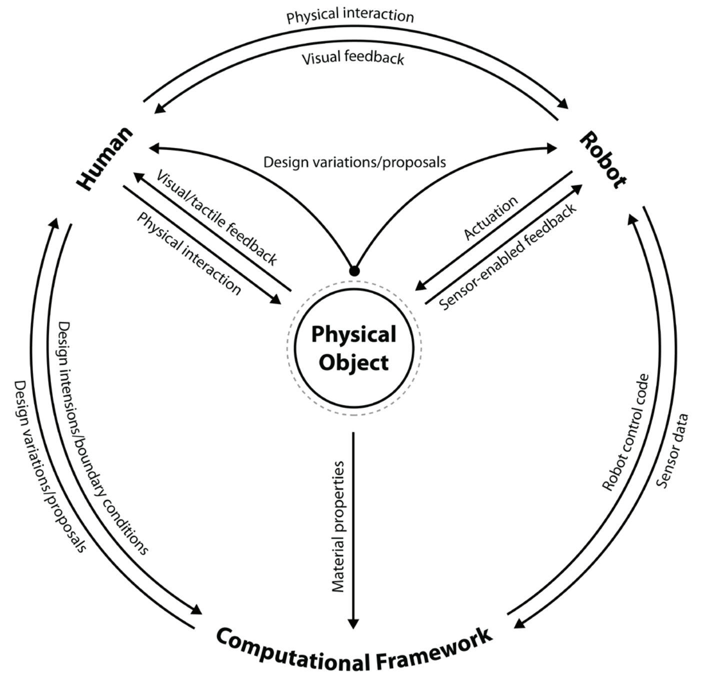


Figure 1.4.
Model of the proposed human-robot design system visualising the information flow between human designer, computational framework, robot, and the physical object/material.
Diagram by Mads Brath Jensen

1.2 Human-Robot Design Systems

To address and clarify the potential challenges and opportunities related to the investigation of robotic fabrication and human-robot interaction and collaboration strategies, a closer examination of the required elements and their potential relations is necessary. Inspired by previous work in robotic fabrication, as referred to above, and based on the previous experience that drives the research motivation, the model in figure 1.4 represents the essential elements and information flows needed to establish a human-robot design system. The proposed model of the human-robot design system is deliberately kept simple to focus attention the overarching features. However, it is essential to appreciate the fact that each of the four main elements (human, robot, computational framework, and the physical object) are comprised by multiple systems and sub-processes stretching into other knowledge domains. Identifying these subordinate systems and uncovering the processes they contain and those they impact upon, is crucial to the inquiry into suitable methods for human-robot design exploration. Investigating the creative impact of engaging with a human-robot design system thereby require an inquiry into aspects of a technical, material, computational, creative, and explorative nature. As not all of these aspects, or their relevance, are known in advance, it is believed that the best method of inquiry involves the design, construction, and exploration of such human-robot design systems.

1.3 Hypothesis and research questions

To address the questions and concerns raised throughout the introduction, the thesis seeks to construct a hypothesis that articulate the premises of the following research endeavour. Based on the research motivation, the hypotheses, together with the more detailed set of research questions below, frames the specific subjects of the study as well as the appropriate research activities and techniques.

> *Robotic fabrication, supported by cyber-physical frameworks for interactive and collaborative processes of human-material-robot making, can support and enhance the creative exploration of design modelling and design making in architecture.*

Based on the hypothesis, the thesis seeks to investigate the following subjects:

> *Q1. How can interactive and collaborative robotic fabrication contribute to the creative 'co-evolutionary' design process?*

In answering this question, it is necessary to consider the impact that such explorative design methods might have on the creative human mind:

> *Q2. How are creative cognitive design processes influenced by interactive and collaborative real-time human-material-robot processes in architecture?*

And, how the proposed design methods might influence and merge with existing design modalities:

> *Q3. What impact does the integration of interactive and collaborative robotic fabrication have on the existing methods and processes supporting creative design exploration?*

Robotic fabrication is primarily driven by technological advancements regarding both hardware and software. Although visual programming environments and available software tools have made robots more accessible for architects, it is important to consider if the technological workflows inherent to the proposed robotic fabrication methods might inhibit design exploration for specific user groups. Therefore it is essential to ask:

> *Q4. What skills and knowledge-sets are required of designers to adopt and implement these technological advancements and their accompanying design processes?*

All of the questions above rely on the realisation and critical evaluation of cyber-physical frameworks and the interactive and collaborative design processes they might afford. For that reason, it is pivotal that the project is capable of answering the following question:

> *Q5. What are the requirements for a robot-based design framework that support interactive and collaborative design processes, and how might this design framework be constructed?*

The main motivation of the thesis stems from the potential of re-introducing human involvement during on-going fabrication processes. The design processes are thereby likely to entail scenarios of human-robot interaction and collaboration made possible through the affordance of a sensing and reacting robotic co-worker. The standard human-to-human design communication thereby needs to be reimagined for questions regarding human-to-robot design communication to be answered:

> *Q6. How can design variations, proposals, and intentions, generated by the computational design algorithm, be applied to the cognitive design creation of the human designer?*

1.4 Objective

As a consequence of the initial motivation, the hypotheses and the more detailed research questions, the general objective of the PhD project is to study how architectural design 'solutions' and design 'problem' processes can be investigated through co-creative robotic fabrication frameworks, which allows for robot-based design methods and processes that respond to human and material behaviour.

On an applied level, the specific objective is to formulate, construct and showcase design methods and design procedures for establishing a direct relationship between the intuitive design processes of the designer and the analytical robotic based evaluation and actuation properties. Construction of the design methods is treated as a continual process centred around the conduction of experiments, involving both prototypes and full-scale demonstrators. The design studies are also critical in understanding how instrumental/informative feedback on design variations can be proposed and implemented in interplay with human design decisions.

1.5 Structure of the Thesis

This thesis is written as a collection of papers comprising two peer-reviewed journal papers (Appendix B and D) and three peer-reviewed conference papers (Appendix A, C, and E). The thesis follows a model in which knowledge is produced through design experimentation and where each forthcoming design study influence one another in sequence. To maintain this sequence, each of the five design studies, disseminated through individual papers, are presented in chronological order. The sequence of papers thereby mirrors the progression of the design studies and their contribution to the overarching research inquiry. Likewise, as each design study challenge the initial research questions, the papers also demonstrate a continuous re-framing of the foundations of the research itself.

Chapter 1 presents the research motivation and outlines how recent technological developments in the field of robotic fabrication are bridging the gap between design modelling and design making. These new possibilities, along with internal motivation, drives the presented hypothesis and the research questions.

Chapter 2 elaborates on the research position and the research design, the latter explaining how a Research-through-Design approach is being implemented and how experimental activities are given a pivotal role during the project.

Chapter 3 outlines the scope of each of the four domains within the proposed design system (see figure 1.3) and elaborates on the theoretical and methodological field associated with each domain. The chapter, seeking to investigate the creative impact of merging these domains into a seamless methodological framework, also attempt to identify existing and potential connections between them.

Chapter 4-6 seeks to answer the research questions through a presentation of the five design studies, each with references to the published/submitted papers. Chapter 4 presents the first two design studies categorised under the heading 'Informed Robotic Design Exploration'. Chapter 5 presents the third and fourth design study categorised under the heading 'Interactive Robotic Design Exploration'. And last, chapter 6 presents the fifth and final design study categorised under the heading 'Collaborative Robotic Design Exploration'.

Chapter 7 intends to present the overall conclusion of the thesis. It includes a summary of the experimental findings followed by answers to the research questions, and finally, a reflection on the results and suggestions for future work.

References

Aish, R. and Hanna, S. (2017) “Comparative evaluation of parametric design systems for teaching design computation,” *Design Studies*. Elsevier Ltd, 52, pp. 144–172. doi: 10.1016/j.destud.2017.05.002.

Bachelard, G. (2002) “Incisive Will and Solid Matter : The Aggressive Nature of Tools,” in *Earth and the Reveries of Will - An Essay on the Imagination of Matter*. Dallas: The Dallas Institute Publications, pp. 27–47.

Bang, A. L. *et al.* (2012) “The Role of Hypothesis in Constructive Design Research,” in *The Art of Research 2012: Making, Reflecting and understanding*. Helsinki, pp. 1–11. Available at: https://www.researchgate.net/publication/276264315_The_Role_of_Hypothesis_in_Constructive_Design_Research/citations.

Boden, M. A. (2004) *The Creative Mind: Myths and Mechanisms*. 2nd editio. London: Routledge.

Braumann, J., Stumm, S. and Brell-Çokcan, S. (2018) “Accessible Robotics,” in Dass, M. and Wit, A. J. (eds) *Towards a Robotic Architecture2*. Applied Research and Design Publishing, pp. 154–165.

Brell-Çokcan, S. and Braumann, J. (2010) “A New Parametric Design Tool for Robot Milling,” *Proceedings of the 30th Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA)*, pp. 357–363.

Brugnaro, G. and Hanna, S. (2019) “Adaptive Robotic Carving,” in *Robotic Fabrication in Architecture, Art and Design 2018*. Cham: Springer International Publishing, pp. 336–348. doi: 10.1007/978-3-319-92294-2_26.

Brugnaro, G., Vasey, L. and Menges, A. (2008) “An Adaptive Robotic Fabrication Process for Woven Structures,” in *ACADIA // 2016 Posthuman Frontiers: Data, Designers, and Cognitive Machines*, pp. 154–163. Available at: http://papers.cumincad.org/data/works/att/acadia16_154.pdf.

Dalsgaard, P. (2017) “Instruments of Inquiry: Understanding the Nature and Role of Tools in Design,” *International Journal of Design*, 11(1), pp. 21–33. Available at: http://www.ijdesign.org/index.php/IJDesign/article/viewFile/2275/758.

Dass, M. and Wit, A. J. (2018) “Robotic Production in Architecture,” in Dass, M. and Wit, A. J. (eds) *Towards a Robotic Architecture*. 1st edn. Novato: Applied Research and Design Publishing, pp. 28–61.

Doerstelmann, M. *et al.* (2015) “ICD/ITKE Research Pavilion 2014-15: Fibre Placement on a Pneumatic Body Based on a Water Spider Web,” *Architectural Design*, 85(5), pp. 60–65. doi: 10.1002/ad.1955.

Dorst, K. and Cross, N. (2001) “Creativity in the design process: Co-evolution of problem-solution,” *Design Studies*, 22(5), pp. 425–437. doi: 10.1016/S0142-694X(01)00009-6.

Dunn, N. (2012) *Digital Fabrication in Architecture*, *Computer*. doi: 10.1007/s00004-012-0130-8.

Edgar, B. L. (2008) “A Short Biography of KR150 L110,” in Gramazio, F. and Kohler, M. (eds) *Digital Materiality in Architecture*. Lars Müller Publishers.

Gramazio, F., Kohler, M. and Willmann, J. (2014) *The Robotic Touch - How Robots Change Architecture*. 1st edn. Zurich: Park Books.

Jensen, M. B. *et al.* (2009) “Material Systems: A Design Approach,” in *27th eCAADe Conference Proceedings*, pp. 721–728.

Jensen, M. B., Kirkegaard, P. H. and Holst, M. K. (2010) *A morphogenetic design approach with embedded structural analysis*, *Proceedings of the International Association for Shell and Spatial Structures (IASS) Symposium 2010*.

Kilian, A. (2006) *Design Explorations through Bidirectional Modeling of Constraints*. Available at: http://www.designexplorer.net/download/Kilian-phd-arch-2006.pdf.

Klinger, K. R. (2008) “Relations: Information Exchange in Designing and Making Architecture,” in Kolarevic, B. and Klinger, K. R. (eds) *Manufacturing Material Effects: Rethinking Design and Making in Architecture*. New York: Routledge.

Leatherbarrow, D. (2005) “Architecture’s Unscripted Performance,” in Kolarevic, B. and Malkawi, A. M. (eds) *Performative Architecture - Beyond Instrumentality*. New York: Spon Press - Taylor & Francis, pp. 5–20.

Macdowell, P. and Tomova, D. (2011) “Robotic Rod-bending,” in *ACADIA 11: Integration through Computation [Proceedings of the 31st Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA)]*, pp. 132–137.

Menges, A. (2008) “Integral formation and Materialisation: Computational Form and Material Gestalt,” in Kolarevic, B. and Klinger, K. R. (eds) *Manufacturing Material Effects: Rethinking Design and Making in Architecture*. New York: Routledge.

Menges, A. (2015) “The New Cyper-Physical Making in Architecture,” *Architectural Design - Material Synthesis: Fusing the Physical and the Computational*, 85(05), pp. 28–33.

Menges, A. and Ahlquist, S. (2011) “Computational Design Thinking (Introduction),” in Menges, A. and Ahlquist, S. (eds) *Computational Design Thinking*. 1st edn. John Wiley & Sons, Inc., pp. 10–29.

Nakamura, J. and Csikszentmihalyi, M. (2005) “The Concept of Flow,” in Snyder, C. R. and Lopez, S. J. (eds) *Handbook of Positive Psychology*. 2nd edn. New York: Oxford University Press, pp. 89–105.

Nicholas, P. *et al.* (2015) “A Multiscale Adaptive Mesh Refinement Approach to Architectured Steel Specification in the Design of a Frameless Stressed Skin Structure,” in *Modelling Behaviour*. Cham: Springer International Publishing, pp. 17–34. doi: 10.1007/978-3-319-24208-8_2.

Nicholas, P. (2018) “Fabrication for Differentiation,” in Daas, M. and Wit, A. J. (eds) *Towards a Robotic Architecture*. 1st edn. Novato, CA: Applied Research and Design Publishing, pp. 76–87.

Oxman, R. (2008) “Digital architecture as a challenge for design pedagogy: theory, knowledge, models and medium,” *Design Studies*, 29(2), pp. 99–120. doi: 10.1016/j.destud.2007.12.003.

Pigram, D. and Mcgee, W. (2011) “Formation Embedded Design,” in *ACADIA 11: Integration through Computation [Proceedings of the 31st Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA)]*, pp. 122–131. Available at: http://papers.cumincad.org/data/works/att/acadia11_122.content.pdf.

Retsin, G., Garcia, M. J. and Soler, V. (2018) “Robotic Spatial Printing,” in Daas, M. and Wit, A. J. (eds) *Towards a Robotic Architecture*. Applied Research and Design Publishing, pp. 126–139.

Tedeschi, A. (2014) *AAD_Algorithms-Aided Design - Parametric strategies using Grasshopper*. 1st edn. Brienza: Le Penseur Publisher.

Terzidis, K. (2006) *Algorithmic Architecture*. Architectural Press, Elsevier. Available at: https://www.academia.edu/5003686/_009801309_architecture_ebook_algorithmic_architecture.

Vasey, L., Maxwell, I. and Pigram, D. (2014) “Adaptive Part Variation,” in *Robotic Fabrication in Architecture, Art and Design 2014*. Cham: Springer International Publishing, pp. 291–304. doi: 10.1007/978-3-319-04663-1_20.

2.

Research Design

Before presenting and arguing for the choice of research design employed in this thesis, it is essential to clarify what research is. In general, research can be defined as "*systematic enquiry whose goal is communicable knowledge*" (Archer, 1995). From this definition, two aspects need further attention. First, the inquiry has to be systematic; it has to be pursued according to a specific plan. This aspect underlines the importance of consciously focusing ones attention on particular information which is extracted from lived experience, and categorised and analysed in a particular way. According to Groat and Wang, this demarcation of information implies that "*all research is reductionist in some form or other.*" (Groat and Wang, 2013). Second, the findings of the research enquiry have to create knowledge, and that this knowledge must be communicated so that others can appreciate it.

In defining the terminology of research design (or strategy), Groat and Wang refer to a passage in which Robert K. Yin states that "*an action plan for getting from here to there*" (Yin, 2003), with 'here' referring to the research questions and 'there' to the findings and their conclusion. This definition points toward a linear process in which the precise steps towards 'there' can be plotted before the research journey begins. However, to address the presented research questions, the project embarks on an explorative investigation to gain new insights about the creative impact of human-robot design processes. Yet to investigate the specific phenomena, it has to be created first. Not until the phenomena is created can it be critically observed. Philosopher of science Ian Hacking, advocates for the creation of phenomena as an essential role of the scientific experiment and argues for the creation of phenomena as the potential pivot of research capable of creating new insights and plotting potential trajectories for further studies (Hacking, 1983). Hence, the ability to support drifting (Redström, 2011) or the pursuit of alternative opportunities (Krogh, Markussen and Bang, 2015) revealed through critical observations of created phenomena is an essential element of the proposed research strategy.

This chapter elaborates on how the thesis positions itself within existing categories of design research, followed by a presentation of the research design, in which the strategies and tactics employed to answer the research questions are argued.

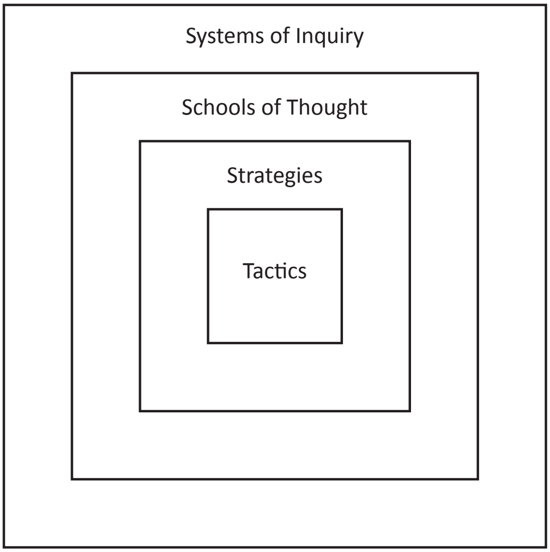


Figure 2.1.
The methodological practices of strategies and tactics are framed by broader systems of inquiry and schools of thought. Diagram based on (Groat and Wang, 2013). Diagram redrawn by Mads Brath Jensen.

2.1 Research position

To specify a set of applied models and methods that enable and support design processes through human-robot co-creation, the thesis is anchors in architecture with connections to computational science, engineering science and psychological science. With the project working across these scientific fields, tapping into each of the respective knowledge fields, the research work incorporates the epistemologies from both quantitative and qualitative science. A positivistic mode of research influences the investigation of physical properties, apparent during the examination of materials and when dealing with processes of robotic systems, both situations treated through objective measurements that assume to reflect reality. On the other hand, when investigating the design method's influence on creative cognitive processes, a constructivist perspective is employed, adopting a subjectivist epistemology in which knowledge emerges as the author, and in some studies also the test subjects, create an understanding of the specific design situation (Groat and Wang, 2013). The studies conducted in the thesis are all based on this integration and simultaneous employment of qualitative and quantitative methods.

As the objective of the thesis calls for the formulation, implementation and evaluation of new design methods, the project relies on the construction of digital and physical prototypes, and thereby depends on practical investigations of experiments performed by the author. According to Archer, these explorations can be categorised as Action Research (Archer, 1995), which he defines as the "*Systematic investigation through practical action calculated to devise or test new information, ideas, forms or procedures and to produce communicable knowledge*" (Archer, 1995). Carrying out research activity through experimental work does, however, imply that the investigator interferes directly with the investigated situation, thereby ruling out truly objective argumentation of the findings. The established research design, therefore, has to make specific reservations towards the evaluation and generalisation of the research findings.

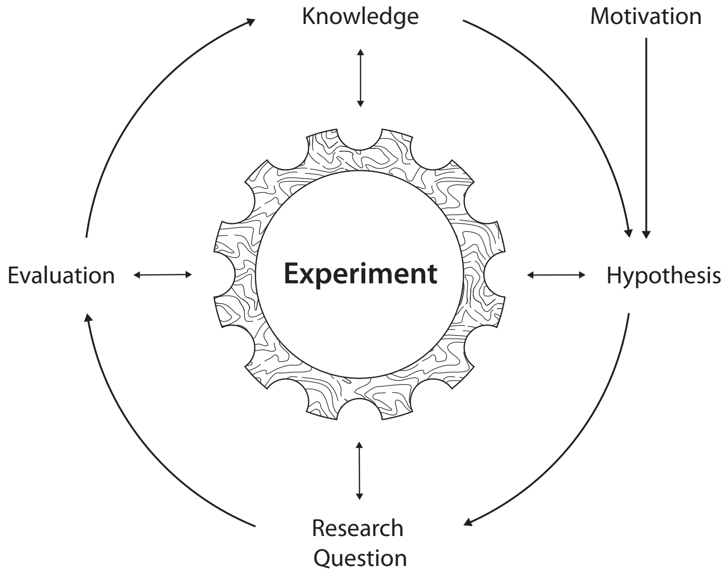


Figure 2.2.
The Constructive Design Research (CDR) model, depicting the constant refram-ing of the research activities centred around conducted experiments. The mod-el is based on the work of (Bang et al, 2012.). Diagram by Mads Brath Jensen.

2.2 Research Design

In the terminology of Groat and Wang, research design is situated within a conceptual framework consisting of four frames, as seen in figure 2.1. The outermost frame refers to the System of Inquiry which describes the researcher's worldview, the assumptions about the nature of reality. These assumptions, as described above, basically distinguish between two systems of understanding, or belief systems: quantitative and qualitative; the first assuming an objective reality in which everything can be measured or weighted (a positivistic view) and the second assumes that multiple subjective realities can be socially constructed (Groat and Wang, 2013). The next frame, referring to the "Schools of Thought", represents the existence of a theoretical perspective, that if adopted, is likely to influence the framing of the research question and the choice of analysis (Groat and Wang, 2013). For the definition of the last two frames, Groat and Wang have adopted the distinction between Strategies and Tactics, as used in military contexts. The choice of strategy thereby refers to the overall plan of the research inquiry, synonymous with the term research design, whereas tactics refer to the selection of specific techniques such as data collection, literature review, performance analysis. Within each of the four concentric frames, multiple choices exist, and although making a specific choice in one frame does not predetermine one's choices in another frame, Groat and Wang underlines the importance of coherence and continuity across the four frames (Groat and Wang, 2013).

As mentioned above, the work presented in this thesis is carried out through the medium of design activities, focusing on the methodology of Research-through-Design (Frayling, 1993; Archer, 1995). This research approach, lately also referred to as Constructive Design Research (Koskinen *et al.*, 2012), advocates for design research being performed through experimental work, i.e. by creatively making objects, interventions, or processes, and evaluating them in the context for which they are developed, with the purpose acquiring knowledge (Bang *et al.*, 2012). Thus, to describe and argue for the chosen research design, a recent model proposed by Bang et al. is applied.

In their recent work, Bang et al. suggest correlating the scientific processes in Research-through-Design with those applied to other research fields, thereby adopting recognised terms to describe the process of knowledge creation (Bang *et al.*, 2012). In their effort to describe constructive design research, they propose a model in which the design experiment has a pivotal role. As shown in figure 2.2, the model, from now referred to as the CDR model, describes a constant reframing of the research activities centred around conducted experiments. The CDR model simultaneously depicts a deliberate hierarchy between Motivation, Hypothesis, and Research Question, based on the conception that "*developing a hypothesis happens on the foundation of a clear motivation, after which a narrower research question can be put forward and criteria for evaluation can be found and used*" (Bang *et al.*, 2012). The last but most important element in the CDR model is knowledge, which is to be disseminated when research has met the defined evaluation criteria. A vital aspect of the CDR model is the type and directionality of the interlinking arrows.

Deduction:

WHAT	**+**	**HOW**	**leads to**	**?**
(thing)		(working principle)		(observed)

Induction:

WHAT	**+**	**?**	**leads to**	**RESULT**
(thing)		(working principle)		(observed)

Abduction 1:

?	**+**	**HOW**	**leads to**	**VALUE**
(thing)		(working principle)		(aspired)

Abduction 2:

?	**+**	**?**	**leads to**	**VALUE**
(thing)		(working principle)		(aspired)

Figure 2.3.
The role of deduction, induction, and abduction in design. Based on (Groat and Wang, 2013).
Diagram by Mads Brath Jensen.

One set of single-headed arrows reveals the continuous cyclical process of reframing the research work, and the other set of double-headed arrows illustrates the experiment's capacity of informing (and being informed) by every level of the research process (ibid). The CDR model thereby facilitates drifting, or the pursuit of alternative opportunities, based on the insights gained from experimental work.

A typology of experimentation

To ensure proper investigation of the ill-defined problems presented in the introduction chapter, the project seeks to establish a research process in which knowledge production is based on insights gained from experimental activities. In doing so, it is essential to clarify how the pursuit of new insights take place and how the experiments are combined. To describe different ways of drifting in Research-through-Design, Krogh, Markussen and Bang describes five different models of knowledge production through design experimentation: *Accumulative, Comparative, Serial, Expansive*, and *Probing* (Krogh, Markussen and Bang, 2015). Although not representing an exhaustive list, their definition of the *Serial* method is very much in line with the explorative approach of this thesis. According to Krogh, Markussen and Bang, the Serial model is defined by design experiments being "*carried out in a certain order or logic of locality determined by how neighbouring experiments in a sequence influence one another*" (ibid, p. 45). With design experiments following each other in chronological order, successive experiments are not only framed by potential solutions or made possible due to the accumulated knowledge but are also motivated based on the identification of new problems. Evaluation of each discrete experiment should, therefore, be based on both the generation of novel solutions and its ability to aid the identification of relevant problems. Complying with the Serial model, the knowledge acquired during an experimental study adjusts and reframes the motivation, hypothesis, and research questions of its predecessor.

Motivation and hypothesis

The project comprises a sequence of five discrete experiments that progressively investigates and identifies new problems and potential solutions. The starting point for this sequence of experiments does not originate in a specific problem but rise from a motivation of exploring the potential advantages in establishing co-creative human-robot design exploration. As such, the motivation contains both the arguments of why the research is relevant to the researcher (internal relevance) and society (external relevance) (Bang *et al.*, 2012).

Following Abraham Kaplan's argumentation for an appreciation for the role of intuition in the generation of a hypothesis (Groat and Wang, 2013) this work views the hypothesis statement as based on intuitive ideas, emerging from previous knowledge, observations, evaluation of experimental work and reviews of relevant literature. The thesis also regards the hypothesis statement as a process of abductive reasoning with the purpose of framing and guiding the research questions (Bang *et al.*, 2012). In doing so, the work engages with the specific form of abductive reasoning that design researcher Kees Dorst refers to as 'Abduction-2' (Dorst, 2011). According to

Dorst, abductive reasoning appears in two forms: 'Abduction-1' and 'Abduction-2', as visualised in figure 2.3. In 'Abduction-1' we are only missing the 'what' (an object, a service, a system) from the equation 'what + how, leads to value', and so represent a form of 'closed' problem-solving. In 'Abduction-2' only the aspired 'value' is known, so the challenge is to create the 'how' (the working principle) and the 'what' (object, service, system) in parallel (ibid, p. 524). This challenge, as stated above, is approached through the strategy of framing, a term defined as: "*the creation of a (novel) standpoint from which a problematic situation can be tackled*" (ibid, p. 525)

Design Experimentation

The design experiment defines the core research activity within this thesis - utilised as a vehicle for reframing both the research questions, the hypothesis, and the motivational aspects associated with the internal relevance of the research. Referring to the CDR model, this thesis does not use experiments to substantiate or falsify a temporary hypothesis, but rather to inform or question it through processes of abductive reasoning, as described above. The act of hypothesising and experimenting thereby becomes a "direction providing" design activity (Bang *et al.*, 2012) that supports a continuous exploration and evaluation of potential challenges. This orientation towards the engagement with physical experiments as a means of knowledge creation, is, according to philosopher of science Manual De Landa, an essential aspect of the experimentalist approach:

> *"In learning by doing, or by interacting with and adjusting to materials, machines and models, experimentalists progressively discern what is relevant and what is not in a given experiment." (de Landa, 2013)*

The learning situation described by De Landa parallels the experimental design processes established in this thesis, in which interaction with physical materials, robotic arms, and computational models combines the act of making with the construction of knowledge. The design experiment thereby supports *knowing-through-action* (Dalsgaard, 2017), the intertwining and co-evolving of thinking and doing, which according to design researcher Peter Dalsgaard, is one out of five qualities of what he labels as the *instruments of inquiry*; the other qualities referred to as *perception, conception, externalisation, and mediation* (ibid.). Dalsgaard's conceptualisation of *instruments of inquiry* is based on Dewey's description of inquiry:

> *"...the controlled or directed transformation of an indeterminate situation into one that is so determinate in its constituents distinctions and relations as to convert the elements of the original situation into a unified whole... The resolution of a problematic situation may involve transforming the inquirer, the environment, and often both. The emphasis is on transformation." (Dewey, 1938)*

According to Dalsgaard, this transformation of the inquirer and the environment is facilitated and affected by the use of tools and technological developments. The work conducted in this thesis, relies on the development of new tools for exploring and transforming the indeterminate situations, and thereby embrace and responds to the constraints, or the 'dual side' as Dalsgaard refers to it, of *instruments of inquiry*, namely that the tools not only extents our capabilities, but also influence our understanding and perception of a situation (Dalsgaard, 2017). During design experimentation, the conceptualisation of *instruments of inquiry* is employed as a framework for supporting the development of novel tools, and their associated methods, and as a way of understanding the role of the proposed instruments within the domain of research inquiry and design creativity.

Besides the instrumental aspect of the research inquiry, the research design also appreciates the importance of the physical objects of the experiments and recognise these as a valid form of knowledge. Robotic fabrication of material prototypes is key to this research endeavour. As the generation of design solutions is, among others, driven by factors concerning environmental performance and contextual specificity, the design outcome is intended to function in the real world. For this reason, much emphasis and research time are assigned to the fabrication of full-scale demonstrators and their exposure to the intended contexts.

As described above, the thesis, as a means of knowledge creation, constructs a series of experimental studies. To uncover the potential influence of human-robot design exploration on creative design processes in architecture, the thesis pursues a strategy in which the experimental studies alternates between author-driven and student-driven design processes. Through this strategy the thesis focus on alternating between subjective and objective observations, an approach adopted to evaluate the robot-based design processes better and to uncover the potential impact of diverse levels of design experience (expert and novice). By conducting two types of studies, the thesis also permits a comparison between two different approaches towards robot-based design exploration. In the first approach, the expert designer in a parallel and feedback-oriented process both develops the human-robot design methods and utilise these methods for exploring design processes and their solutions. In the second approach, the novice design students are asked to follow a proposed human-robot design method and develop design solutions within the constraints of the given problem-space. By conducting the latter approach through the teaching environment of the design studio, the mutual problem investigation between the researcher and the students provides a forum for speculative ideas within a short, but intensive, period (Roggema, 2016).

Observations

As mentioned above, knowledge acquisition is approached through two distinct approaches – author-driven and student-driven design experimentation. This allows for two perspectives on the investigation of the research objective and at the same time demands that the design researcher alternate between two distinct types of observation.

During author-driven design experimentation, the focus is on identifying the barriers and enablers of the creative design process and how the construction of human-robot design methods might take these findings into account. In such explorative design investigation, a specific kind of observation is required. According to Hacking, the design researcher is “*not the ‘observer’ of traditional philosophy of science, but rather the alert and observant person*” (Hacking, 1983). The observer must, therefore, focus on identifying the unexpected, the errors, and the processes that bring new learning or distort what was already thought to be known. This entails that during the iterative process of constructing, testing and observing design experiments, emphasis should be placed on “*the mechanisms by which this might be occurring, rather than how much it is occurring*” (Robertson and Radcliffe, 2009).

In the student-driven design studies, the role of the observer is deliberately more distanced from the design process. As suggested by Robertson and Radcliffe, it is essential to focus on the qualitative aspects of the design process, which can be ensured through qualitative observations performed by the author, a strategy that is applied and discussed in Design Study 2 (Chapter 4). However, it is also believed that triangulation between subjective observations, data-gathering, and questionnaires constitutes a strategy that affords a more nuanced insight into the cognitive design processes of the human designer, while still accounting for the more data-driven aspects of robotic co-creation. Based on an appreciation of the interplay between subjective and objective processes in human-robot design exploration, Design Study 4 (Chapter 5) employs a triangulation of qualitative user observations, questionnaires, and quantitative logging of individual student design processes.

Evaluation

As discussed above, critical observations of the design processes, both author- and student-driven, enabled by the construction of co-creative human-robot design methods, is one of the evaluation methods employed to assess the design methods and frameworks proposed during the thesis. However, the design methods and frameworks themselves are also seen is as tools for evaluation. The proposed co-creative design methods, enabling explorative processes of parametric-driven variation and robotic-based fabrication, allows for continual assessment of design solutions and are thereby also seen as tools for evaluation. While the making and evaluation of such digital and physical prototypes allow for an understanding of the relationships between processes related to generation, simulation, evaluation, fabrication, and assembly, the physical establishment of full-scale demonstrators acts as a critical object for evaluation as it allows for post-construct analysis and evaluation in a specific context.

Seeking to establish a research process in which knowledge production is based on insights gained from experimental activities, it is essential that the proposed co-creative design method, design tools, demonstrator and the student-driven design processes, are all evaluated and discussed in relation to their potential for driving further research inquiries.

2.3 Results and dissemination

The findings of the research inquiries are presented and discussed based on five design studies conducted within the period of the PhD project. Each design study has been disseminated through peer-reviewed channels; Design Study 2 and 4 through journal papers (Appendix B and D), and Design Study 1, 3, and 5 through conference papers (Appendix A, C, and E). The findings and discussions presented in this thesis targets researchers, designers, and architects either working or interested in the field of robotic architecture, creative design thinking and computational design. As a result, the work has been disseminated through journals and conference supporting these research fields.

The structure of the research design follows a serial method in which identified problems and their potential solutions frames and motivates successive design experiments. As this is an intrinsically non-linear research process, the findings do not converge towards a single solution and an indisputable result, but as a consequence, the results of the thesis constitute a documentation of a process. In conveying these design processes, the knowledge revealed in prototypes and demonstrator is crucial, and as a result, much attention has been allocated towards the exhibition of this scientific work.

References

Archer, B. (1995) "The Nature of Research," *Co-design, Interdisciplinary journal of design*, pp. 6–13. Available at: https://archive.org/details/TheNatureOfResearch.

Bang, A. L. *et al.* (2012) "The Role of Hypothesis in Constructive Design Research," in *The Art of Research 2012: Making, Reflecting and understanding*. Helsinki, pp. 1–11. Available at: https://www.researchgate.net/publication/276264315_The_Role_of_Hypothesis_in_Constructive_Design_Research/citations.

Dalsgaard, P. (2017) "Instruments of Inquiry: Understanding the Nature and Role of Tools in Design," *International Journal of Design*, 11(1), pp. 21–33. Available at: http://www.ijdesign.org/index.php/IJDesign/article/viewFile/2275/758.

Dewey, J. (1938) *Logic - The Theory of Inquiry*. New York: Henry Holt and Company, Inc.

Dorst, K. (2011) "The core of 'design thinking' and its application," *Design Studies*. Elsevier Ltd, 32(6), pp. 521–532. doi: 10.1016/j.destud.2011.07.006.

Frayling, C. (1993) "Research in Art and Design," *Royal College of Art Research Papers*, 1(1), pp. 1–5. Available at: http://researchonline.rca.ac.uk/384/3/frayling_research_in_art_and_design_1993.pdf.

Groat, L. and Wang, D. (2013) *Architectural Research Methods*. 2nd editio, *Architectural Research Methods*. 2nd editio. John Wiley & Sons, Inc.

Hacking, I. (1983) "The creation of phenomena," in *Representing and Intervening*. Cambridge University Press, pp. 220–232. doi: 10.1017/CBO9780511814563.017.

Koskinen, I. *et al.* (2012) *Design Research Through Practice*. Elsevier. doi: 10.1016/C2010-0-65896-2.

Krogh, P. G., Markussen, T. and Bang, A. L. (2015) "Ways of drifting—Five methods of experimentation in research through design," *Research into Design Across Boundaries*, 1, pp. 39–50. doi: 10.1007/978-81-322-2232-3_4.

de Landa, M. (2013) *Intensive Science and Virtual Philosophy*. Bloomsbury Academic.

Redström, J. (2011) "Some notes on program/experiment dialectics," in *Proceedings of Nordes'11 the 4th Nordic Design Research Conference, Making Design Matter!*, pp. 1–8.

Robertson, B. F. and Radcliffe, D. F. (2009) “Impact of CAD tools on creative problem solving in engineering design,” *CAD Computer Aided Design*. Elsevier Ltd, 41(3), pp. 136–146. doi: 10.1016/j.cad.2008.06.007.

Roggema, R. (2016) “Research by Design: Proposition for a Methodological Approach,” *Urban Science*, 1(1), p. 19. doi: 10.3390/urbansci1010002.

Yin, R. K. (2003) *Case study research - design and methods*. 3rd editio. London: SAGE Publications Inc.

3.

Fields and Domains

As described in the Introduction chapter, the general objective of the PhD project is to investigate, formulate and evaluate design methods that facilitate co-creative human-robot design exploration. This research agenda is pursued by carrying out inquiries within a network of distinct knowledge fields comprising human cognition and creativity, technological advancements in robotic simulation and fabrication, architectural performance aspects, design thinking, computer science, and sensor-based feedback systems. As illustrated through the model in figure 1.4, one can conceive the scope of this multidimensional field as a framework consisting of four general domains, each associated with an existing research field.

To investigate the creative impact of merging these domains into a seamless methodological framework, it is crucial to accumulate relevant theoretical and methodological aspects associated with each field, and equally important, to clarify existing and potential connections between them. As the majority of the research investigation is located in the development of the computational framework and the means with which it supports creative design processes, the following chapter concentrates on attaining relevant theoretical and methodological knowledge, first from the field of Design Thinking and Creativity, and then from Computation in Architecture. The field of Creative Robotics, briefly presented in the Introduction chapter, is also discussed and relevant knowledge concerning the project’s use of diverse material systems is discussed within the individual design studies presented in chapter 4, 5 and 6.

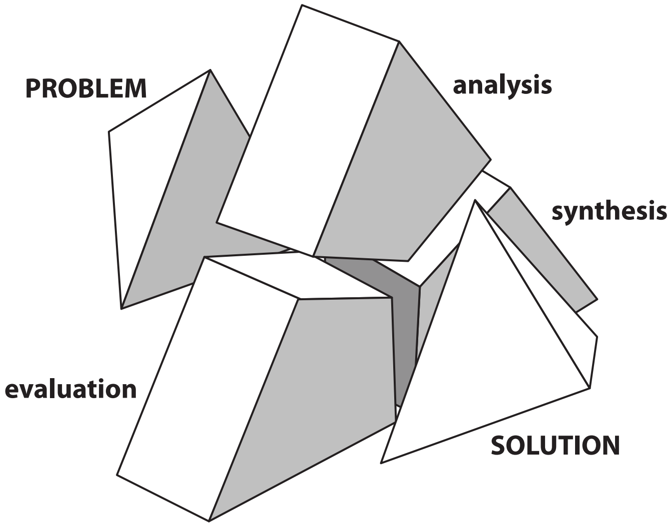


Figure 3.1.
Bryan Lawson's map of the negotiation between problem and solution through the three activities of analysis, synthesis, and evaluation. Illustration based on (Lawson, 2005), redrawn by Mads Brath Jensen.

3.1 Design Thinking

Design, as an activity, is performed by all people, from the simple act of arranging toys on a shelf, selecting matching clothes for a new outfit, planning the weekly calendar or preparing exquisite meals. To some degree, these everyday design activities share some of the same tasks as the ones occurring in the creative activities of professional designers.

The most simple design tasks often merely involve the selection and combination of existing items. Most of the daily design activities occur without even being recognised as a design task. Other design tasks include the creation of new things, which in exceptional cases are so novel and surprising that they will be recognised, and perhaps copied by others (Lawson, 2005). However, the last example is much more likely to occur as a result of the design activities of professional designers. Another critical difference is that professional designers design for other people. As within the field of architecture, the design task likely involves a broad set of constraints and features many unclear and wicked problems, requiring a wide range of skills. To understand the actual process of designing, the following section elaborates on current design methods and theories and how computational processes can support these.

3.1.1 A Formal Model of Design Exploration

As hinted above, the professional designer is often confronted with design tasks that contain ill-defined problems and features large sets of constraints with many viable solutions. This challenge is indeed the case for the architectural profession, where designing a building requires finding solutions for several multi-disciplinary aspects. For example, the final design solution for a building needs to ensure its construction and adherence to current building regulations. It also needs to utilise current advances in building technology and fulfil all the wishes of the client. Furthermore, it must address the changing problems of the urban 'system' and deal with the environmental changes of the future. Just to name a few of the issues that require utilitarian consideration. Many issues are also interrelated - changing how the design responds to one problem is likely to affect its treatment of other issues. Integrating an increasing number of considerations during the architectural design process has led to a complexity increase that challenges the cognitive load imposed on the designer. Professor of Architecture, Bryan Lawson, has discussed this challenge. Based on his many observations of designers at work, he authored the book 'How Designers Think' and termed this issue a *"multidimensional design problem"*. He exemplifies the dilemma through the design of a window:

> *"As well as letting in daylight and sunlight and allowing for natural ventilation, the window is also usually required to provide a view while retraining privacy. As an interruption in the external wall the window poses problems of structural stability, heat loss and noise transmission, and is thus arguable one of the most complex building elements."* (Lawson, 2005)

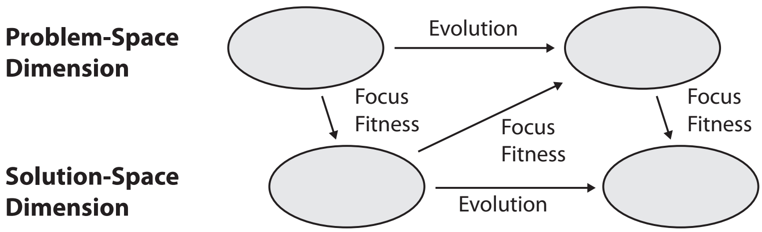


Figure 3.2.
The co-evolution model, illustration based on (Maher, 1994), redrawn by Mads Brath Jensen.

One of Lawson's arguments is that as a designer, one cannot think separately on each design problem as they must all be satisfied within the same solution. This argument highlights one of the main challenges in integrated design, having to respond to a growing number of requirements results in a very complex set of interrelated constraints that are in themselves often dynamic. Additionally, a suggestion often put forward when discussing architectural design processes is the importance of addressing related challenges as early in the design process as possible, thereby ensuring their integration and avoiding post-amendments on the final solution. Technological means, costs, norms, client requests, and similar requirements constitute what can be called performance-driven requirements. These requirements are also what Hillier, Musgrove and O'Sullivan labelled as the *"external variety reducing constraints"* (Hillier, Musgrove and O'Sullivan, 1972). Together with a designer's cognitive capabilities, the *"internal variety reducing constraints"* serve as limiting factors on the space of possible solutions. Hillier, Musgrove and O'Sullivan also suggested including conjecturing as an active part of the design process. They argued that it could proceed side by side with the action of problem specification – a core strategy of their conjecture-analysis model.

In Lawson's seminal work on design thinking, he discusses the problem-solution space and argues that these two spaces emerge together in parallel during the design process. Lawson suggests that the negotiation between problem and solutions involves three main activities: analysis, synthesis and evaluation - with no indication of the sequence of these activities, nor any fixed starting point (see Lawson's map in fig 3.1.). While Lawson's map visualises the activities supporting the exploration of the problem-solution space, it refrains from treating the aspect of time and therefore says little about how the negotiation process might evolve.

In 1994 Mary Lou Maher, Professor of Design Computing, suggested a cognitive model for co-evolutionary design featuring two parallel search spaces; the problem space and the solution space (Maher, 1994). Maher's model introduces "*an approach to design problem solving in which the requirements and solutions of design evolve separately and affect each other*" (Maher and Tang, 2003) and incorporates time through the progression of specific reiterated exploration processes (see fig 3.2.). The co-evolution model is supported by the work of Kees Dorst, Professor in the field of design thinking, and Nigel Cross, Professor and author of the book 'Designerly Ways of Knowing'. The two authors used the model to explain the behaviour found in their protocol studies of experienced designers regarding the nature of creativity in design (Dorst and Cross, 2001). Through their work, they found that designers could fixate the temporarily unstable problem-solution space by exploring and identifying what they labelled as 'bridges' between the problem space and the solution space, also referred to as a matching problem-solution pair. Dorst and Cross further suggested that the development of matching problem-solution pairs can be achieved through *"…developing and refining together both the formulation of a problem and ideas for a solution, with constant iteration of analysis, synthesis and evaluation processes between the two notional design 'spaces'…"* (Dorst and Cross, 2001). Dorst and Cross thereby indirectly suggest a combination of Maher's model and Lawsons'

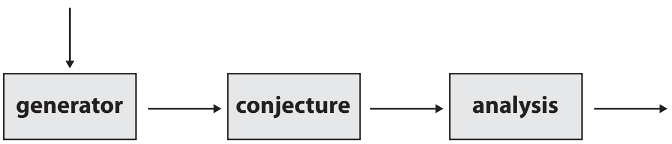


Figure 3.3.
Jane Dark's map of the design process, based on (Lawson, 2005), redrawn by Mads Brath Jensen.

map, with the first defining how to transition between the two design spaces. The latter describes the activities that allow for the interchanging of new information between these spaces.

Exploration of the Problem-Solution space – establishing relations

To kick-start explorative negotiation between the two design spaces, the use of conjecturing has been proposed. Still, the challenge of how to initiate the process remains. Based on interviewing expert designers (in this case, well-known British architects), Jane Darke suggested the idea of *"primary generators"* (Darke, 1979) as a way of using a simple idea to narrow down the range of possible solutions allowing the designer to perform the analysis-evaluation-synthesis routine described by Lawson. Darke proposed that the primary generator, also referred to as the "organising principle" in the later work of Peter G. Rowe (Rowe, 1986), could be used as the initiating element for the conjecture-analysis model by Hillier, Musgrove and O'Sullivan. In Jane Dark's map of the design process (see figure 3.3), the primary generator thereby represents an aspect of the problem that the designer, with the current knowledge of an often ill-defined design problem, finds essential. Based on this aspect, the designer develops a rough solution that is examined to make further discoveries about the given design problem.

The exploration of design conjectures can be performed through the use of one or several alternative modes of designing ranging from the traditional processes of hand sketching (ex. representational drawings or more diagrammatic illustrations) to the making of physical models or prototypes (by use of both analogue and computer-controlled tools), or as in more contemporary practice through the use of CAD software for both generation and simulation of design suggestions. Each design mode holds different sets of potentials and limitations and can be selected based on what best suits the exploration of the current conjecture. Often, however, the selection is based on the designer's skill set and previous experience.

Current advancements in computational architecture have led to the establishment of new design modes with the potential of supporting the exploration of design problems while allowing the designer to maintain and control higher levels of complexity. Two design modes can be defined, computational design and computational simulation, the first focusing on the generation and design of virtual objects and the other on examining these design suggestions through an imitative representation of physical systems or processes.

One of the main benefits of utilising computational design for exploring architecture is the opportunity to establish relations (or rules) between design variables. Referring back to Lawson's example of the complexities of the window, one could, for instance, introduce simple rules governing the relationship between a series of windows, ensuring that the desired surface area is always achieved. Setting up a network of such relations allows the designer to ensure constant compliance with specific requirements, freeing up cognitive capacity for pursuing other design aspects. Computational design exploration allows the designer to make conjectures in a digital environment and analyse the design solutions based on visual feedback, thereby supporting an iterative analysis-evaluation-synthesis exploration to establish problem-solution pairs. If geometrically describable, these abstract 'bridges' can be defined as new parametric relationships within the computational model and lead to new restrictions to be established by the designer. This process potentially results in the generation of new geometric elements, new even to the designer. The newly defined relationships store the detected problem-solution pair. Based on this redefinition of the problem-solution space, what Maher would define as moving through one complete cycle of co-evolution, new and more informed explorations are achievable.

Although computational technology and the associated methods of computational design allow for an exploration of complex design tasks, they also present limitations on the design exploration. One of the main advantages of computational design also constitutes its inherent disadvantage – namely the digital virtuality. By enabling the construction of a wide variety of digital models, the digital realm allows for exploring all imaginable shapes and compositions. However, the gap between the imaginary digital world and the more "restricted" physical world can be challenging to bridge. The introduction of computational simulation is one method for bridging this gap. By exposing the generated geometry to a simulation of gravitational forces, sunlight radiation, acoustic sound rays, fabrication processes, and other relevant criteria, the digital design solutions evolve, based on approximation, to the forces and restriction of the physical world. Computational simulation thereby enables the designer to evaluate (computational) design suggestions based on their simulated environmental performance, allowing for an analysis-evaluation-synthesis routine based on more performance-driven information. The informed evaluation of design suggestions is, of course, a considerable advantage in the field of architecture. It equips the designer, already from the initial design process, with methods, tools and techniques for evaluating the expected environmental impact of proposed design solutions, creating a knowledge-base for further conjecturing.

The design methods mentioned above and their theoretical underpinning offer insight into 'how designers think' and the steps that one might follow to produce a design solution that responds to and solves a specific design problem. This methodological insight is crucial for the current investigation of how robotic fabrication might become an integrated element in a design process. It reveals the inherent design activities and their potential for being incorporated in robotic based design processes. The aim of integrating robotic technology within an architectural design process is not to automate the design process or to make it more efficient but rather to support and enhance the creative and explorative aspects of designing. To better understand the thought processes involved in creative design processes and creative thinking, the following section elaborates on creativity and the cognitive processes associated with this field.

3.1.2 Creative Cognitive Design Processes in Architecture

As the thesis investigates the creative impact of integrating co-creative robotic design exploration within the early design process, the following section seeks to extract applicable models and terms from research on creativity, forming a base for the discussion of co-creative human-robot design methods.

What is creativity?

Scientific interest in the field of creativity was reawakened as a side effect of the 2nd World War and the cognitive challenges confronted by the U.S. Air Force. At that time, the escalation of World War II had forced aeroplane technology to advance, resulting in a more complicated working of these airborne war machines. Consequently, these technological advancements led to a severe incline in pilot errors, often with tragic losses of life and machinery. The specific challenge that faced the U.S. Air Force occurred when pilots were exposed to a sudden unforeseen emergency. In these situations, the pilots, even those with a high IQ score, were unable to react appropriately to the unexpected situation, or in other words, to generate novel solutions for the problem at hand. At that time in history, IQ tests were the conventional measure of intelligence and, together with physical tests, the criteria for selecting potential pilots. Recognising the deficiencies of the current test, the U.S. Air Force assigned J. P. Guilford, a professor of psychology, to lead the development of new methods for testing creativity (Csikszentmihalyi, 2014c). The work by Guilford and his team identified nine specific intellectual abilities crucial for army pilots (The Standard Nine Project), and in addition, the results of the research project generated new momentum for further studies of creativity – making it a popular topic within psychology research.

Although the field of creativity received great scientific attention during the last half of the 20th century, a single unified definition does not yet exist. Regardless, creativity can be defined as a mental process that, on some mysterious and unconscious level, is exposed to sudden moments of discovery, the ‘aha’ moment, leading to novel and valuable solutions (Jones, 2012). Despite the apparent unpredictability of the creative process, creativity is typically defined as bringing into being an idea, an artefact, or a performance that is both original (contains novelty), valued (is deemed useful), and implemented (Csikszentmihalyi and Wolfe, 2014).

During the 1980’s Mihaly Csikszentmihalyi, Professor of Psychology and Management at the University of Chicago, developed a conceptual model called the Systems Model of Creativity (Csikszentmihalyi, 2014c). Based on Csikszentmihalyi’s accounts, the model was conceived as a reaction to the findings from a follow-up on a longitudinal study of students from the School of the Art Institute of Chicago, performed during his doctoral thesis two decades earlier. This follow-up study showed that some of the most promising and gifted art students had not established themselves as creative artists or found employment in a creative line of work. A result that led Csikszentmihalyi to conclude that creativity *“…could not be understood unless one took into account the impact a person had in his or her community of peers; its causes could*

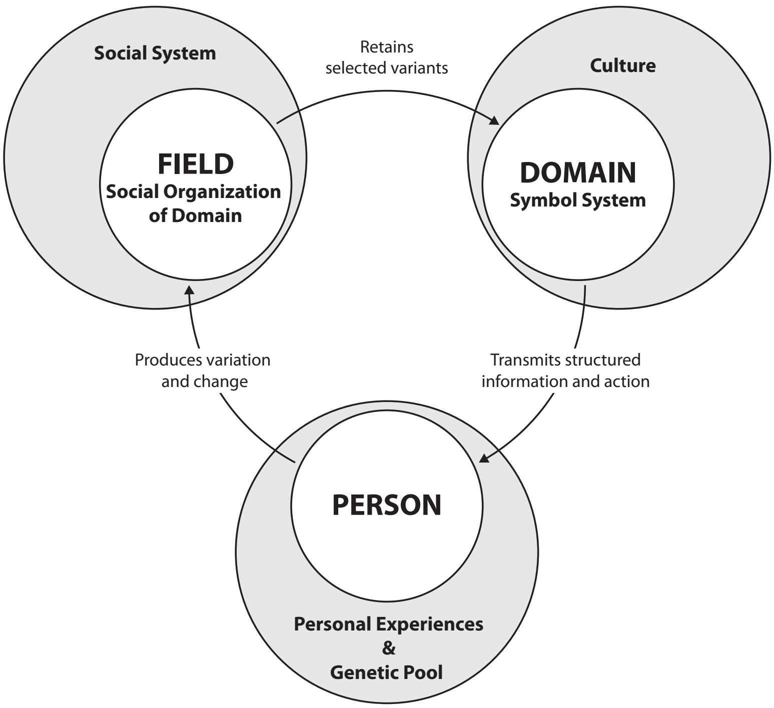


Figure 3.4.
A systems view of creativity. This map shows the interrelationships of the three systems that jointly determine the development of a creative idea, object, or action. The individual takes information provided by the culture and transforms it, and if the change is deemed valuable by a field, it will be included in the domain, thus providing a new starting point for the next generation of creative persons. The actions of all three systems are necessary for creativity to occur (Csikszentmihalyi, 2014b).
Diagram redrawn by Mads Brath Jensen.

not be understood without taking into account the traditions from which the novelty came, and the contribution society made to the individual's ideas." (Csikszentmihalyi, 2014c). Csikszentmihalyi further suggested that creativity cannot result from individual actions alone, but that it occurs as the product of three main shaping forces; **the field** consisting of a social organisation or a group of 'gatekeepers' that selects ideas worth preserving; **the domain** which preserves and transmits the ideas for following generations; and **the individual** who generates new ideas within the domain. In Csikszentmihalyi's view, creativity can thereby be defined as a phenomenon that occurs from the interaction between these three shaping forces, a phenomenon he named: 'The Systems Model of Creativity' (Csikszentmihalyi, 2014b). The best way to explain this model is through the diagram depicted in figure 3.4, which represent the relationships between the three central systems in circular causality. Each system affects the others and is affected by them in response. In Csikszentmihalyi's view, creativity is best understood in a broad perspective where the results of individual making (a person producing variation) can only be recognised as 'creative' if it is judged so by the field (the gatekeepers of the discipline) and has reached implementation in the (cultural) domain (Csikszentmihalyi, 2014a).

Adopting a systems model of creativity equips the PhD project with a model for understanding creative ideas as derived from information 'inherited' from associated domains. For example, a variation proposed during the thesis is only stored in the domain if recognised as promising by the field (in this case, the appointed assessment committee). However, the systems model seems less suitable for comprehension and critical evaluation of the creative human-robot design methods investigated during this thesis. As mentioned in chapter 2, the PhD project seeks to answer the proposed research questions by completing consecutive design studies, aiming to develop, explore, and evaluate design methods for creative human-robot design processes. In these studies, the focus is directed towards the cognitive processes and the design-related thought patterns associated with the person(s) interacting with a robotic fabrication process. This focus emphasises creativity as perceived by the designer and not on creative contributions recognised by a social field and dependant on many extraneous factors – of which a person has no control. To accommodate the investigation and evaluation of personal creativity during design exploration processes, the theoretical foundation needs to elaborate on the cognitive aspects of creativity.

Types of Creativity

Although the work of Csikszentmihalyi focuses on defining creativity as a social construction, a phenomenon that results from the interaction between the three systems; person, field, and domain, he also shows an interest in individuals displaying actions that can be recognised as being highly creative. This interest motivated him, in collaboration with Associate Professor Jeanne Nakamura, to propose a dichotomy between creativity with a capital C (cultural creativity) and with a lowercase c (personal creativity) (Csikszentmihalyi and Nakamura, 2006). According to Csikszentmihalyi and Nakamura, Cultural creativity, or big C, refers to the ideas or products deemed original, creative, and valuable by the social field and included in the cultural domain – in other words, creativity as defined by the 'Systems Model of Creativity'. Personal creativity, or small C, refers to any novel ideas or experiences that a person can have and which only have to be considered creative in the consciousness of the person who has had them. This definition is clearly stated by the two authors when describing small c, "*For personal creativity, no external evaluation is necessary; only the subjective experience matters.*" (Csikszentmihalyi and Nakamura, 2006). The vital aspect of personal creativity is that, unlike cultural creativity, it is an experience that everyone can obtain. Although similar to cultural creativity, small c is still a type of creativity that one has to learn to develop; and according to Csikszentmihalyi and Nakamura, curiosity is the one trait necessary for both types of creativity (Csikszentmihalyi and Nakamura, 2006).

Like Csikszentmihalyi and Nakamura's definition of cultural creativity and personal creativity, Margaret A. Boden, Research Professor of Cognitive Science at Sussex University, proposed a distinction between what she calls two different senses of 'creative'. Boden suggests that one sense is psychological (P-creative) and concerns ideas found to be surprising, or even novel, to *the individual mind* that generates the idea. The other is historical and concerns ideas that are novel to *human history* (Boden, 2004). P-creative and H-creative ideas have many similarities with small C and Big C creativity, respectively. However, being very occupied with the creativity of the human mind, Boden explores the nature of P-creative ideas in more detail.

When describing the qualities of P-create ideas, it is essential to emphasise that they do not have to be novel to anyone else than the person generating them; the emergence of a novel P-creative idea might even be predictable for an outside party, but this does not make the idea less creative (Boden, 2004). This aspect is crucial for the evaluation of the design studies conducted in this thesis, as the results of applying new design methods for human-robot design exploration needs to be critically assessed based on the capacity to support creative processes on a personal level. Thus, ideas generated by one person during a design process does not have to be novel to another person evaluating them; they might even be anticipated. By recognising the emergence of P-creative ideas as a crucial aspect in the evaluation of creative human-robot design processes, one must also question which cognitive processes that allow these creative ideas to happen and how to trace these differences. In other words, instead of only asking if an idea is creative or not, one should also ask how creative it is? This approach would allow for further evaluation of the proposed design methods and the forms of creative thinking they potentially support.

Three forms of creative thinking

In an attempt to differentiate the psychological processes that allow people to generate creative ideas, Margaret Boden has proposed three forms of creativity: *combinational creativity*, *explorational creativity*, and *transformational creativity* (Boden, 2004). These three forms not only represent different thought processes, they also act as three levels of increasing creativity – ranging from the simple combination of ideas to the complicated process of transforming the existing style of thinking.

Boden defines *combinational creativity* as the "*...unfamiliar combination of familiar ideas*" (Boden, 2004). The process of combining existing ideas can be caused by deliberate thought processes, by unconscious thought processes, or they can even be generated based on random processes. As the generation of novel ideas is based on the combination of ideas familiar to the person generating them, the process requires a large inventory of knowledge or past experiences (the importance of experience is further elaborated below). To ensure that peers value the resulting idea to be novel it has to 'make sense', and the peers must be able to establish a connection between the included ideas; which is why random combinations a rarely recognised as novel.

Explorational creativity involves an exploration of the conceptual spaces in a person's mind. Conceptual spaces are defined by Boden, as "*structured styles of thought…normally picked up from one's own culture or peer group, but are occasionally borrowed from other cultures.*" (Boden, 2004). The size of the conceptual space can vary based on previous experience, but no matter the size, coming up with a novel idea within the restrictions of a specific style of thinking is termed creative in an exploratory way. Exploring a conceptual space can be compared to exploring a structured geographical area, like a city or a landscape. One might explore the shopping streets or the city's narrow alleys or drive down to a lake in a forest to find a perfect spot for a coffee break. All of these things already exist but goes unnoticed if one is not in an exploratory mode. Professional scientists and architects, amongst many other disciplines, often perform explorations of their mental maps in a search for new experiences and new ideas within a given conceptual space; exploring these spaces long enough and one might discover new potentials and even start to be aware of their limits.

Transformational creativity occurs when a person realises the limits of a given conceptual space and decides to transform that space. Most frequent, these transformations result in small alterations or minor tweaks to the landscape. At other times, and often associated with H-creative ideas, a new road is introduced (the equivalent of establishing a new technique or method) or in rare cases, the existing motorway is re-routed, as when Charles Darwin proposed his theory of evolution by natural selection which eventually changed the conceptual space for all people (Boden, 2004). The emergence of transformational creativity in a person's mind requires that the person is capable of changing the restrictions of the existing style of thought, allowing for new thoughts that were not possible before.

> *"In many ways, then, mental exploration is like the land-based variety. But there is one crucial difference. Mental geography is changeable, whereas terrestrial geography is not."* (Boden, 2004)

The three forms of creativity proposed by Boden allows for critical insight into the form and nature of creativity, and her work provides definitions that can support the interpretation and appreciation of the creative processes that occur during robotic-based design exploration. Based on Boden's accounts on creativity, one can argue that the creation of human-robot design methods must promote design processes that aid the designer in understanding and exploring the conceptual spaces of his/her mind. Having gained an understanding of what creativity is and what forms of creative processes new human-robot design methods might give rise to, the following section aims to uncover the cognitive processes involved in the generation of these creative ideas.

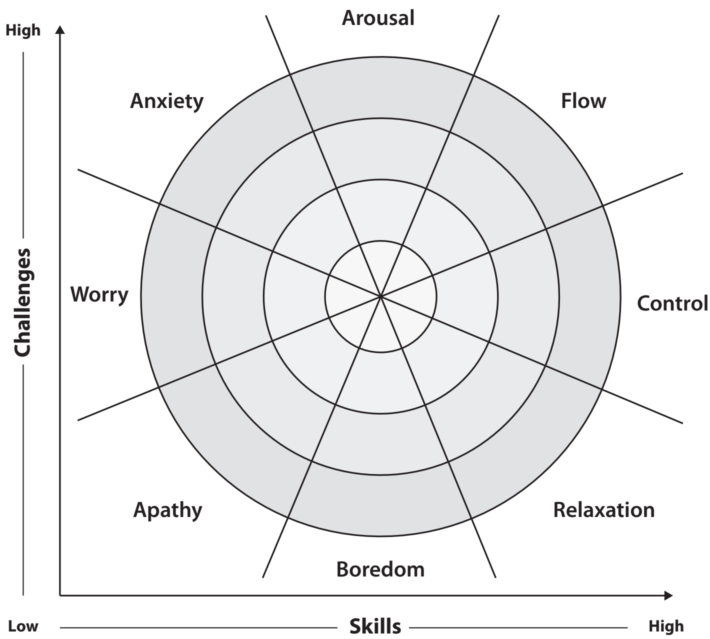


Figure 3.5.
Model of the flow state. Flow is experienced when perceived challenges and skills are above the actor's average levels; when they are below, apathy is experienced. Intensity of experience increases with distance form the actor's average levels of challenge and skill, as shown by the concentric rings. Model from (Nakamura and Csikszentmihalyi, 2005), redrawn by Mads Brath Jensen.

Cognitive processes in creative thinking

The field of psychology provides a wide range of literature describing the psychological factors that either facilitate or impair creativity. Personality studies have shown that creative people tend to be independent, risk-seeking, and open to new experiences (Csikszentmihalyi, 2014a). One of the most dominant characteristics of creative individuals is curiosity, also described as a being intrinsically motivated, or as possessing a constant enthusiasm for experience (Guilford, 1967). Other prominent attributes found in creative individuals is divergent thinking, a term coined by J. P. Guilford during the development of the Standard Nine Project (Getzels and Csikszentmihalyi, 1976), and discovery orientation, a behaviour observed in studies conducted by two of the leading figures in the study of creativity J. W. Getzels and M. Csikszentmihalyi (Csikszentmihalyi, 2014a). Divergent thinking is a cognitive style measured by fluency, flexibility, and originality of mental operations, whereas discovery orientation is defined as the *'…tendency to find and formulate problems'* (Csikszentmihalyi, 2014a). Although the level of creativity associated with the exploration of design problems inevitably depend on the personality and behaviour of the person performing the design task, the aspect of measuring and scoring creativity is outside the scope of this thesis. Instead, the focus is directed towards the cognitive processes and thought patterns involved in creative thinking, as well as the occurrence of creative flow and the importance of design experience.

To gain a better understanding of creative thinking, the findings from research in the field of psychology should be substantiated by research carried out from within the field of architecture and design. The work of Bryan Lawson provides one such design-based perspective. One of the creative abilities that gains clarification by being examined from 'within' the design field is divergent and convergent thinking, as mentioned above. According to Lawson, Guilford treats this binary division as two separate and independent dimensions; the rational and logical processes of convergent thinking associated with abilities in science, and the intuitive and imaginative processes of divergent thinking associated with skills in the art (Lawson, 2005). According to Lawson, this separation of the two styles of thinking has led to confusion where convergent thinking is seen as a measure of intelligence and divergent thinking as creativity. Although he recognises that on a general level design problems, due to their open-ended approach, can be seen as divergent tasks, he also emphasises that design processes entail many steps, of which some contains convergent tasks.

> *"… it would be absurd in the extreme to pretend that there are no parts of design problems which are themselves amenable to logical processes and have more or less optimal solutions. Design clearly involves both convergent and divergent productive thinking and studies of good designers at work have shown that they are able to develop and maintain several lines of thought in parallel."* (Lawson, 2005)

Regarding the design methods proposed in this thesis project, being aware of the alternation between convergent and divergent tasks, which are likely to occur during a creative human-robot design process, allows a critical evaluation of how such methods influence and support creative design thinking.

While investigating creativity in design, Lawson detected another cognitive pattern associated with design thinking, namely the ability for designers to change the direction of their thinking (Lawson, 2005). This ability allows for the generation of more ideas, thereby enhancing the possibility of discovering better solutions to a given problem. The process of investigating a given idea is associated with a specific cost, including time expenditure and consumed mental energy. As a result, a large effort is required to change the direction of such cognitive processes and on a mental level 'abandon' previously acquired ideas. For the studies conducted within this PhD project, the proposed design methods are investigated through the completion of design processes conducted within a pre-defined problem-solution space, for instance restricted by a particular material system, a specific robotic fabrication method, or a fixed method for computational simulating of a chosen environmental performance. These design restrictions are likely to affect the designer's freedom for radically changing the direction of his/her creative thinking. This should not be seen as a negative aspect, as the pre-defined restrictions on the problem-solution space is expected to focus the design exploration and, to a higher degree, inform the generation of design solutions with regards to its physical making and environmental performance. However, in evaluating design methods for creative human-robot design exploration, it should be considered to what extent the method restricts the designer's ability to change the direction of thinking.

According to Lawson, the ability to change the direction of thinking is closely related to two different approaches in design thinking which he defines as 'generation of alternatives' and 'parallel lines of thought' (Lawson, 2005). Designers following the first approach generates many ideas, often with high variance and only a few shared attributes. This process is followed by a selection procedure where the best idea, or a combination of features from the top-ranked ideas, are chosen. This approach entails that the direction of thinking is highly scattered as the designer deliberately forces his/her thought process into different directions. Referring back to Maher's theory concerning co-evolution of the problem- and solution space, as well as Dorst and Cross's introduction of problem-solution pairs, the generation of alternatives can be seen as a way of mapping out the 'terrain' of the solution space. On the other hand, the second approach deals with a 'parallel line of thought' and involves only one design idea on which the designer simultaneously investigates several aspects of the same design. This approach entails that the designer deals with the examination of several open-ended aspects in parallel, without resolving these too early in the design process, as this prevents influence and interaction across the parallel investigations. The relevance of working with several parallel lines of thought has been identified in a study of design protocols conducted by Colin Rowe, which led him to describe the use of several primary generators for directing the design process.

> *"In this case study, several distinct lines of reasoning can be identified, often involving the a priori use of an organising principle or model to direct the decision-making process."* (Rowe, 1986)

To support and strengthen the robotic-based design framework proposed in this thesis project, it is crucial that the proposed design methods support the potential advantages of parallel lines of thought. The development of an interactive human-robot framework must support design processes where multiple aspects, related to geometric variation, environmental performance, fabrication techniques, assembly, and aesthetics, are investigated simultaneously. By supporting, and hopefully also strengthening the designer's ability to allow multiple parallel investigations to take place, the proposed human-robot design method, as well as the conducted design processes, must also critically relate and respond to the questions of whether these computer and robot-aided design systems help or hinder such cognitive processes.

In the case of working with multiple parallel lines of thought, or with several primary generators as mentioned by Rowe and described in more detail later on, the analogy of juggling seems appropriate. An architect, similar to a juggler, must operate several aspects simultaneously, and if one slips out of focus, it will drop, and the process is impaired (Lawson, 2005). Anyone experienced with the act of juggling knows that it is mentally demanding and that it requires a certain speed; oscillating the objects very quickly is often the only way of keeping them all in the air (and in mind). Similar to juggling, designers often describe parallel exploration of multiple design aspects as an intensive activity (Lawson, 2005) which at moments can be so mentally consuming that designers find themselves absorbed by the process, forgetting about time and place – a state of mind that Csikszentmihalyi and Wolfe termed 'creative flow'.

Creative Flow

The theoretical foundation of flow originates from the study of intrinsic motivation, or autotelic activity, defined as an activity that is rewarding in and of itself (*auto* = self, *telos* = goal). Based on multiple interviews with chess players, rock climbers, dancers, surgeons, and others, Csikszentmihalyi found that the reported subjective experience of their intrinsic motivation and enjoyment of the activities were similar across play and work settings (Nakamura and Csikszentmihalyi, 2005). It was further argued that flow exist in almost all activities, for some people in painting a wall, riding a bike, sweeping the sidewalk, or playing a game of chess. On the other hand, the exact same activities might be seen as boring or even appalling to others – "it is the subjective challenges and subjective skills, not objective ones, that influence the quality of a person's experience." (Nakamura and Csikszentmihalyi, 2005).

As being in a state of flow can be intrinsically rewarding, individuals having experienced it often seek to achieve it again. In the case of playing a game, experiencing the engaging, challenging and rewarding process, impels one to try it again, and for this second time now with increased skills and knowledge of the game. Furthermore, if a game is well-developed, it provides increasingly complex challenges, thereby sustaining the right amount of challenge for the growing skills of the individual playing the game. Flow activities can thereby be recognised as fostering growth, and according to Csikszentmihalyi, a flow activity *"…typically also provides a system of graded challenges, able to accommodate a person's continued and deepening enjoyment* *as skills grow.*" (Nakamura and Csikszentmihalyi, 2005). However, measures developed and used in flow research, including qualitative interviews, questionnaires, scales for measuring flow, and the development of the Experience Sampling Tool (ESM) (Nakamura and Csikszentmihalyi, 2005), has shown that the notion of merely balancing out skills and challenges, is not an adequate approach to ensuring flow. To amend this shortcoming, Fausto Massimini, Professor at the University of Milan, together with his colleagues, introduced the notion of skill stretching and redefined flow as "the balance of challenges and skills *when both are above average level for the individual."* (Nakamura and Csikszentmihalyi, 2005). As seen in the model of the flow state in figure 3.5, this redefinition allows creative flow to be mapped as eight different experiences, each one related to a specific cognitive experience within the challenge/skill space. The concentric rings inside each octant represent an increase in the intensity of the perceived experience. Being in the outer ring of the 'Flow' octant is thereby considered desirable, whereas being in the outer ring of the 'Apathy' octant is undesirable. ESM studies aiming to measure autotelic personality (Hektner and Asakawa, 2000) has also shown that enjoyment is high for both high challenge, high skill experiences ('flow' and 'arousal' octants) and low challenge, high skill experiences ('control' and 'relaxation' octants). From current understanding of human evolution, these two strategies for survival; one expansive and energy-consuming, the other conservative and energy-saving, has likely led to preferred human behaviour and selected throughout generations. While at the opposite side avoiding being powerless ('anxiety' and worry' octants) and without purpose ('apathy' and 'boredom' octants) has been preferable traits (Nakamura and Csikszentmihalyi, 2005).

In describing the concept of flow into more detail, Csikszentmihalyi's has defined the following conditions and characteristics for flow (Nakamura and Csikszentmihalyi, 2005):

Condition:

A. *Perceived challenges, or opportunities for action, that stretch (neither overmatching nor underutilising) existing skills; a sense that one is engaging challenges at a level appropriate to one's capacities.*

B. *Clear proximal goals and immediate feedback about the progress that is being made.*

Characteristics:

A. *Intense and focused concentration on what one is doing in the present moment.*

C. *Merging of action and awareness.*

D. *Loss of reflective self-consciousness (i.e., loss of awareness of oneself as a social actor)*

E. *A sense that one can control one's actions; that is, a sense that one can in principle deal with the situation because one knows how to respond to whatever happens next.*

F. *Distortion of temporal experience (typically, a sense that time has passed faster than normal).*
G. *Experience of the activity as intrinsically rewarding, such that often the end goal is just an excuse for the process.*

For the aim of developing a design method that integrates robotic technology to enhance computational and physical exploration of material systems and their making, it is imperative that the implementation of robotic fabrication does not inhibit the creative process. To support this aim, flow theory provides a set of distinct conditions and characteristics for fostering flow experiences and thereby clarify essential aspects for the creation and evaluation of a proposed robotic-based design method. Additionally, the model of flow states (depicted in figure 3.5) provides a segmented view of the eight cognitive states, and their intensity, that an individual can experience when exposed to different levels of challenges and skills. Knowledge about these experiential states affords a critical approach towards the design activities enabled by the proposed design method and to what degree they provide the designer with opportunities for 'designerly' actions that match the skillset of the individual designer.

The development of skills

In the above exposition of flow theory 'skills' is used as the ability needed for an individual to meet the challenges associated with a present task. Skills can be defined as doing or acting in practice, which includes both motor skills and cognitive skills; learning a skill requires training and practice, but also knowledge about how to perform a task (Baartman and de Bruijn, 2011). Knowledge about how to do something thereby forms the foundation for the ability to develop and apply skills.

Knowledge can be defined as the cognitive processing and retaining of information and can be seen as the sum of a person's experiences. The importance of knowledge on creativity is stressed by Boden in her effort to present (and remove) some of the myths associated with this cognitive ability:

> *"What makes the difference between an outstandingly creative person and a less creative one is not any special power, but greater knowledge (in the form of practised expertise) and the motivation to acquire and use it."* (Boden, 2004)

It is essential to notice that Boden differs between acquiring and using knowledge. Using one's existing knowledge and practised skills to solve a given task doesn't necessarily imply the acquisition of new knowledge. With sufficient knowledge and skill-set people are generally capable of solving a task without thinking; the knowledge has become internalised and automated, what Schön refers to as tacit knowledge (Schön, 1983). However, if something unexpected happens, people can either react by ignoring the problems (leading to no new knowledge) or by thinking and acting upon these problems and through reflection on the actions gain new knowledge (Baartman and de Bruijn, 2011). The differences in acquired knowledge thereby imply that if presented with a design problem, an expert designer might only need to rely on tacit knowledge to solve the task. In contrast, serious thinking needs to be performed by a novice designer. The levels of personal design experience and relevant knowledge are thereby more than likely to affect the generation of new ideas when adopting and following a new design method. As pointed out by Hakak et al. while reviewing creativity in architecture: "*Experiences indirectly affect creativity. The larger the inventory of experiences, the more and better combination of ideas is possible*" (Hakak, Biloria and Venhari, 2014). Seeking to understand how collaborative human-material-robot processes influence creative cognitive design processes in architecture (see 'Q1' in chapter 1.3) it is thereby crucial to consider the creative and cognitive capacity of the test subject. As described in chapter 2, the thesis seeks to address this situation by conducting two types of studies; one in which the author (expert designer) is simultaneously developing and designing with the proposed design method, and another in which students of architecture (novice designers) are asked to follow the proposed design method.

As the thesis seeks to investigate the potential of interactive and collaborative human-robot design processes, it emphasizes on the importance of merging physical and material-based design exploration with digital generation- and simulation-based design processes. An unfolding of the relationship between the development of bodily skills and the use of tools is therefore important. In exploring the idea of craftmanship Richard Sennett, Centennial Professor of Sociology at the London School of Economics elaborates on "*what the processes of making concrete things reveals to us about ourselves*" (Sennett, 2008). Sennett argues, similar to Baartman and de Bruijn that the development of skills begin as bodily practices in which knowledge is gained through movement and touch, supported and guided by existing knowledge. Sennett continues this argument by suggesting that dealing with resistance and ambiguity, originating among others from imperfect or incomplete tools, can be seen as instructive experiences allowing bodily skills to develop through creative processes. In exploring design methods for human-robot co-creation, it is thereby important to incorporate ambiguity and facilitate a rethinking of both the digital and the physical tools to deal with these resistances. An open, adaptable computational framework and an engagement with tools that are technologically easy-accessible and structurally simple and interchangeable, might ensure human-robot design processes that accommodate a learning process that incorporates and exploits tacit knowledge.

In seeking to establish design methods that support the physical interaction between human, robot, and material system, the human hand is likely to be the most important link between the designer's mind and the tools developed and applied within the physical design system. Further examination of the grip and touch of the human hand and the effect it has on the mental aspects of skill development is therefore appropriate. As a starting point, it is important to note that the act of gripping - and of letting go again - is a voluntary action, in contrast to the involuntary blinking of the eyelids. According to ethnologist Mary Marzke, gripping is an action that can be sorted into three basic types: pinching an object, cradling an object, and cupping an object (Marzke, 1997). As gripping an object can be linked to a conscious action, so can actively touching an object be seen as a conscious intent that supply the brain with sensory input. According to Sennett, the fingers can also engage in an unconscious probing touch; an action referred to as “localized” touch (Sennett, 2008). A common example of this unconscious probing action is the casual touching, or probing, of one’s neck while being engaged in another conscious activity, as reading a book. Only if the fingers stumble upon something unexpected (ex. an unnoticed scratch) will the sensory feedback become evident in the conscious mind. The continuous storing of information in the brain based on hand movements and sensory input facilitates an interplay within the neural network of the hand-eye-brain, for instance assisting the brain in predicting the weight, shape, and feel of objects (Sennett, 2008). The body thereby holds the ability to anticipate ex. the movements needed for grasping of an object and can act in advance according to visual input; a phenomenon called *prehension*.

In the case of building skills it is important to note that anticipation is not an innate skill, but a set of fit-for-purpose actions acquired through the encounter of wrong moves, false starts and dead ends, which through reflection leads to increased understanding. Or in other words, prehension is the result of sustained practice. In cases where complex skills become deeply ingrained, the tacit knowledge allows a person to experience what the philosopher Maurice Merleau-Ponty has described as “being as a thing” (Merleau-Ponty, 2013). In these situations, one might experience the feeling of being so absorbed in acting that the actual bodily movements become an unconscious act. Consciousness is focused on what one sees and no longer on what one’s hands are doing. Based on this definition, the exploration of human-robot co-creation might engage with the phenomena of prehension based on two opposing tactics. First, designing methods that give rise to human-robot interactions in which fit-for-purpose actions can be acquired (allowing unconscious actions to emerge). Second, designing methods in which unpredicted robotic movements trigger new experiences – stimulating the development of new skills.

Creativity and tools

As mentioned above, the all-absorbing and tacit experience of “being as a thing” often occur through the skilled use of tools. In processes of making, the skills of the human hand are often extended through tools that are either designed for a specific task, what Sennett refers to as fit-for-purpose tools, or for aiding in multiple situations, in which case they are referred to as all-purpose tools (Sennett, 2008). Most people, having tried to use a hammer to drive a nail into a piece of wood, will be able to recollect the initial experience of having to apply full focus to accurately, and with sufficient force, swing the hammer to the desired position (many of us probably also recollect the pain of not having adequate skills to succeed in this endeavour). Through continuous repetition, this simple action can be practised to a level where the improved skillset allows the focus to transfer from the swinging of the hammer to the nail piercing the wood; even to such a degree where the action enables the trained person to feel the resistance of the wood through the tool and precisely adjust the force of consecutive strokes. When tools challenge us - either because they are difficult to handle or because they do not quite fit the job – they give rise to an important learning process. As mentioned above the challenge posed by the tool can either be met by practice through repetition – repeating and action again and again until it is mastered – or by adapting the form of the tool to make it a better fit for a specific purpose. The last case is of specific interest to the work conducted in this thesis project, as it encourages a co-evolution of human skills and the tools associated with both the physical robotic setup and the digital design system. It is essential that the thesis project, and the proposed design methods, bring about a deeper understanding of how analogue and digital tools can engage us in exploring new design possibilities.

In exploring design methods for human-robot-material co-creation, the scope of the scientific work can be defined as involving two types of tools: the physical robotic arm with attached end-effector(s) and the digital tool(s) established through CAD software. Based on this scope, the thesis project can be considered as having a *"willingness to see if a tool or practice can be changed in use"* (Sennett, 2008). This attitude is defined as the first of four stages for how 'intuitive leaps' happen, as accounted for by Sennett. Besides intention, this first stage also draws on established skills and a sense of untested possibilities to allow for reformatting of the tool/practice.

The second stage occurs when different domains are brought together to establish an adjacency. In the thesis project, this can be exemplified through the bringing together of the deterministic and repetition-focused domain of robotic fabrication with the non-deterministic and explorative domain of design creation.

The third stage refers to the experience of surprise. When comparing the results of bringing together the domains, initial assumptions might be proven wrong or merely inadequate, and something unexpected and exciting is revealed.

Sennett refers to the last stage as gravity; emphasizing that in the transferal of skills and practices between domains, unresolved problems will still exist. However, Sennett also stresses that although newly discovered techniques, tools or methods might carry new problems, they also provide new insights.

Through the definition of the four stages involved in making an intuitive leap: reformatting, adjacency, surprise, and gravity, Sennett seeks to show that the experience can indeed be crafted and that tools can aid in driving this creative experience. Sennett also states that:

> *"Both limited and all-purpose instruments can enable us to take the imaginative leaps necessary to repair material reality or guide us toward what we sense is an unknown reality laden with possibility."* (Sennett, 2008)

Naturally, it is the expectation of this thesis project to establish design methods capable of facilitating and crafting such intuitive leaps.

Creativity and brain science

> "In the long run, brain science may also provide clues to the nature of creativity itself." (Kandel, 2012), page xvii.

In the previous discussion regarding the importance of prehension, a difference between conscious and unconscious mental processes was linked to the accumulation of bodily skills and tacit knowledge. It was further described how consciousness shifted from focusing on hand movements and tool handling towards the visual and tactile perception of the material object. To better understand the relative roles of conscious and unconscious processes, as well as their effect on creativity and decision making, this section seeks to provide a more in-depth insight into the field of modern brain science.

To examine how the brain works, we can start by realising just how our brain allows us to understand the world around us, or in other words how our brain creates an internal representation of the world. In this regard, we can turn to the cognitive psychologist Chris Frith who writes:

> *"What I perceive are not the crude and ambiguous cues that impinge from the outside world onto my eyes and my ears and my fingers. I perceive something much richer – a picture that combines all these crude signals with the wealth of past experience… Our perception of the world is a fantasy that coincides with reality."* (Frith, 2007)

Frith's account of perception as being the combination of 'crude signals' and 'past experience' is concurrent with the definition of bottom-up and top-down information, as described by University Professor and Nobel Prize winner Eric R. Kandel.

Bottom-up information is defined as "*supplied by computations that are inherent in the circuitry of our brain*" (Kandel, 2016). Biological evolution has enabled our brains to extract key elements from the sensory information it receives from the external world. The inborn rules that govern our visual system allow our brains to compute and extract features such as contours, intersections and crossing of lines, enabling us to discern and recognize people, faces, and objects.

Top-down information, on the other hand, refers to mental functions such as imagery, attention, and expectations - in other words, the previous experience and knowledge possessed by the individual person. According to Kandel, the processing of top-down information allows us to resolve the ambiguities that remain from the bottom-up processes (Kandel, 2016). The combination of these two mental processes allows the brain to perceive objects, even in situations where the information is incomplete. This process is exemplified through the image of The Dalmatian Dog in figure 3.6, where bottom-up processing allows the brain to perceive various densities of black areas from which contours and shapes can be extracted. Combined with existing knowledge of animals and their respective shape/composition a dog is identified. The acknowledgement that our perception of the outside world is the result of our brains computation of 'crude signals' and 'past experience' has led Kandel to state

Figure 3.6.
The Dalmation Dog (Photographer: Ronald C. James)

that "*visual perception is not a simple window on the world, but truly a creation of the brain*" (Kandel, 2016).

Parallel to the two-step scheme of bottom-up and top-down processing of visual information, recent insights suggest that conscious and unconscious processes play different roles in decision making and creative thinking (Kandel, 2012). The Dutch social psychologist Ap Dijksterhuis, argues that, since a great deal of memory is unconscious, this mental process is superior to conscious processes when dealing with decisions that require the simultaneous comparison of many alternatives. Based on the results of decision-making experiments conducted by Dijksterhuis and Meurs (Dijksterhuis and Meurs, 2006), Kandel also argues that:

> *"Conscious thought works from the top down and is guided by expectations and internal models; it is hierarchical… unconscious thought works from the bottom up, or non-hierarchically, and may therefore allow more flexibility in finding new combinations and permutations of ideas."* (Kandel, 2012)

In their designed experiments Dijksterhuis and Meurs also explored the notion *set-shifting*; the transition that occurs when we distract ourselves and our thought processes shift from a convergent perspective to a divergent perspective. From the results of comparing different groups of participants, they found that introducing distractions, thereby allowing the mind to wander, encouraged unconscious bottom-up thought processes. Additionally, based on the emergence and detection of new solutions, the result also suggests that distractions allowed a shift towards new top-down processes that were based on different knowledge or other previous memories (Kandel, 2012).

Kandel's definition of the bottom-up and top-down information processing taking place in the brain, as well as the different roles of conscious and unconscious thoughts, point towards the importance of set-shifting and intentional distraction as a means for enhancing the emergence of creative ideas and novel solution. While ensuring a creative flow during design exploration, with reference to the work of Csikszentmihalyi, might be seen as stressing the importance of conscious thinking, the work of Kandel and Dijksterhuis/Meurs advocate for periods of regression and relaxation to exploit the, in some cases superior, power of unconscious thought processes. One scenario, in which an active implementation of 'set-shifting' and 'intentional distraction' might enhance idea generation, is within the continuous iteration between computational design processes, physical prototyping, material studies, and robotic fabrication. The shifting between multiple 'design modes' might, rather directly, support the occurrence of set-shifting. A second scenario could reside within the forced pauses that are likely to occur during turn-taking between human and robot; while waiting for the robot to sense or act on the material system, the mind of the human participant might drift into unconscious thoughts.

3.1.3 Summary

This chapter on 'Design Thinking' elaborates on existing methods of design thinking and their theoretical underpinning, thereby offering an insight into "how designers think" and identifying a set of existing design modes that support the integration of human-robot co-creation. In addition, a study of creativity, and the cognitive processes associated with this field, is conducted and applicable theoretical models and relevant terminology extracted, forming a foundation for the discussion of co-creative human-robot design methods. The study allows for critical insight into the form and nature of creativity and provides definitions that can potentially aid the construction, interpretation and appreciation of the creative processes that are likely to occur during robotic-based design exploration. The study identifies several important aspects to be addressed in the investigation and creation of methods for co-creative human-robot design exploration; these aspects include the support of parallel lines of thought, the fostering of flow experiences, the relation between the development of bodily skills and the skilled use of tools, and the creative potential present in implementing prehension to actively deal with conscious and unconscious mental processes.

3.2 Computation in Architecture

Having discussed the essential theoretical and methodological aspects of creative thinking in architecture, we now have a sound understanding of the cognitive processes vital to the creation and investigation of new human-material-robot processes in architecture. Referring to the model of the proposed human-robot design system in figure 1.4, the previous section on design thinking has sought to unfold the cognitive processes of the human designer to understand how these might connect to the other three elements. This section presents current research in computational design and discusses its relevance for creative exploration and physical realisation of architecture.

The era of computation in architecture began with a system called Sketchpad, a Computer-Aided Design (CAD) system developed by Ivan Sutherland. Regarding the importance of the Sketchpad system, Sutherland stated that: *"The Sketchpad system, by eliminating typed statements (except for legends) in favor of line drawings, opens up a new area of man-machine communication."* (Sutherland, 1963). Although a bold statement, one must acknowledge his claim, as two decades later the technology had been made affordable, and with the release of AutoCAD in 1982, it was made accessible to the field of architecture. In the following decade technological developments allowed computational software to gain momentum and creation and representation of 2D drawing cross over into 3D modelling, thereby changing the way architects could imagine, view and communicate their ideas. Aiming to add more information to the 3D models and increase the efficiency and integration of otherwise separated tasks and disciplines (Rowe, 1986), platforms for building information modelling (BIM) was invented. What is important to realise is that, although the advancement in 2D CAD drawing, 3D modelling, and BIM supported architects in performing their work, by introducing more efficient routines, easier access to structured information, and better representations of solutions through increased graphical facilitation, these technologies actually didn't aid the design process, they aided the documentation of it (Wujec, 2017).

In the 1990's the approach to digital architecture shifted towards algorithmic driven design processes in which focus was no longer engaged directly with the modelling of specific shapes, but instead on the mathematical equations and parametric sequences driving the generation of architectural shapes. This shift towards computational thinking highlights the use of logical methods and procedures of calculation, as well as a heightened awareness of the mathematical descriptions and algorithmic procedures that forms the otherwise invisible computational background. As an elaboration on different levels of computational utilisation in architecture is essential for understanding how computational thinking influences the investigations conducted in this thesis, this is presented in more depth later in this chapter.

During the last two decades, the exploration and implementation of computational processes have also been driving the area of rapid prototyping. Technological developments in the field of computer numerical controlled (CNC) machining tools (such as laser cutters, milling machines, 3D printers, and robotic arms) paralleled by the advancements of computational and parametric design software, has enabled an "integrated proof of concept for building components" (Rowe, 2017) and allowed for systematic integration of fabrication strategies and material properties.

Although designers, by harnessing the technological advancements of computers and CAD software, by utilising algorithmic and parametric procedures, and by rapidly prototyping possible design solutions, can solve and visualise increasingly complex design tasks at an increasing pace, it is crucial to investigate what impact computational design has on the theory and methodology of design thinking, as described in chapter 3.1.

3.2.1 Computational Design Thinking

Design thinking in a digital age

In 1987, Peter G. Rowe published his ground-breaking book Design Thinking, in which he provided a systematic account of architectural design thinking based on his detailed observation of designers in action. Thirty years later, Rowe held a lecture at the Harvard University Graduate School of Design in which he reappraised his earlier work, by offering a new account of 'design thinking' describing *"…ways in which the capacities of the digital age have changed the way perceive and understand creative problem-solving in architecture*" (Rowe, 2017). Rowe points to four areas of design thinking where considerable contributions of the digital age are prominent.

The first concerns the increased variety of representational techniques, which, according to Rowe, leads to higher degrees of precision. The graphical techniques available in current software allows for natural alternation between sectional presentation and three-dimensional perspectives, both with several rendering options. This precision in graphical representation Rowe arguments can help in revealing incompleteness and thereby guide further structuring of the problem-space, leading to a more directed search of this problem-space.

The second area originates from the iterative power of generate-and-test procedures, with numerous design outcomes being generated and tested through various computational techniques. Rowe arguments that the generation aspect allows observation of a broader array of satisfactory outcomes, and also allows for an exploration of complex architectural geometries that would not otherwise have been feasible (Rowe, 2017). The increasing generative potential of existing design software, to a large degree powered by the processing speed of modern computers, can be seen in architectural projects that range from the generation of 'simple' geometric design outputs by the thousands, to iteratively re-generating updated versions of a very complex geometry or set of geometries.

The third area relates to the testing aspect of these generate-and-test procedures. Today's computational design environments features acknowledged methods for evaluating and simulating various aspects of a building's performance, relating to structural, material, and environmental aspects, among others. Rowe stresses that the contribution not only rests on the fact that these methods are known inside their respective knowledge domains, but that the adoption of computational design approaches has made it possible to incorporate several of these evaluation methods within the computational environment (Rowe, 2017). The relevance of these methods to the quality of design thinking, Rowe believes to be twofold: *"…including improved efficiency and raised levels of certainty and understanding around the phenomena being assessed, which, in turn, can be reflected in better guidance for further problem-solving.*" (Rowe, 2017).

The fourth area relates to the enhancement of access to information from various areas of domain knowledge (Rowe, 2017). The digital age has contributed to improvements in many domains within or related to architecture, such as building materials, wind flow, thermal performance, indoor lighting, and interaction of people. Access to these knowledge domains has similarly improved due to digital means of communication and sharing of information.

Thereby, according to Rowe, the contributions of the digital age on design thinking, has improved the capacities for manipulation, iteration, assessment, and informational search; leading to an increase in available computational techniques for decision-making in architecture, providing designers with methods and tools that allow for a faster and more in-depth examination of problem—solution spaces, resulting in more focused search areas and potentially better design outcomes (Rowe, 2017). Rowe's last point about increased capacity for digitally searching and retrieving information from related, or even remote, research domains is a general contribution of the digital age that has affected not just the field of architecture, but all fields of research, creative or non-creative. Particularly for the work conducted in this thesis, access to domain knowledge regarding aspects related to robotic engineering, psychology, design thinking, visual analysis, and thermal and acoustic simulation, has been crucial for informing many of the core problem-solving activities.

Digital design models

The remaining three areas of contribution are more specific, but not restricted, to research in computational design thinking. Their importance was captured more than a decade earlier, in 2005, by Rivka Oxman, Professor and researcher in the field of Digital Design, Cognition and Computation, as she proposed a conceptual framework for the emerging field of digital design (Oxman, 2006). Based on an extensive analysis of recent developments in architecture, including the work of Frank Gehry on the Guggenheim Museum in Bilbao, the International Terminal at Waterloo Station by Nicholas Grimshaw, and the Yokahama International Port Terminal by Foreign Office Architects, Oxman traced the emerging phenomena of digital design. By proposing a generic schema for models of design, Oxman illustrates how the paper-based model of design differs from five distinct classes of digital design models. Through an explication of the six different models, four of them depicted in figure 3.7, the information flow and the typical interactions between the designer and traditional design activities as representation, generation, evaluation, and performance, could be identified.

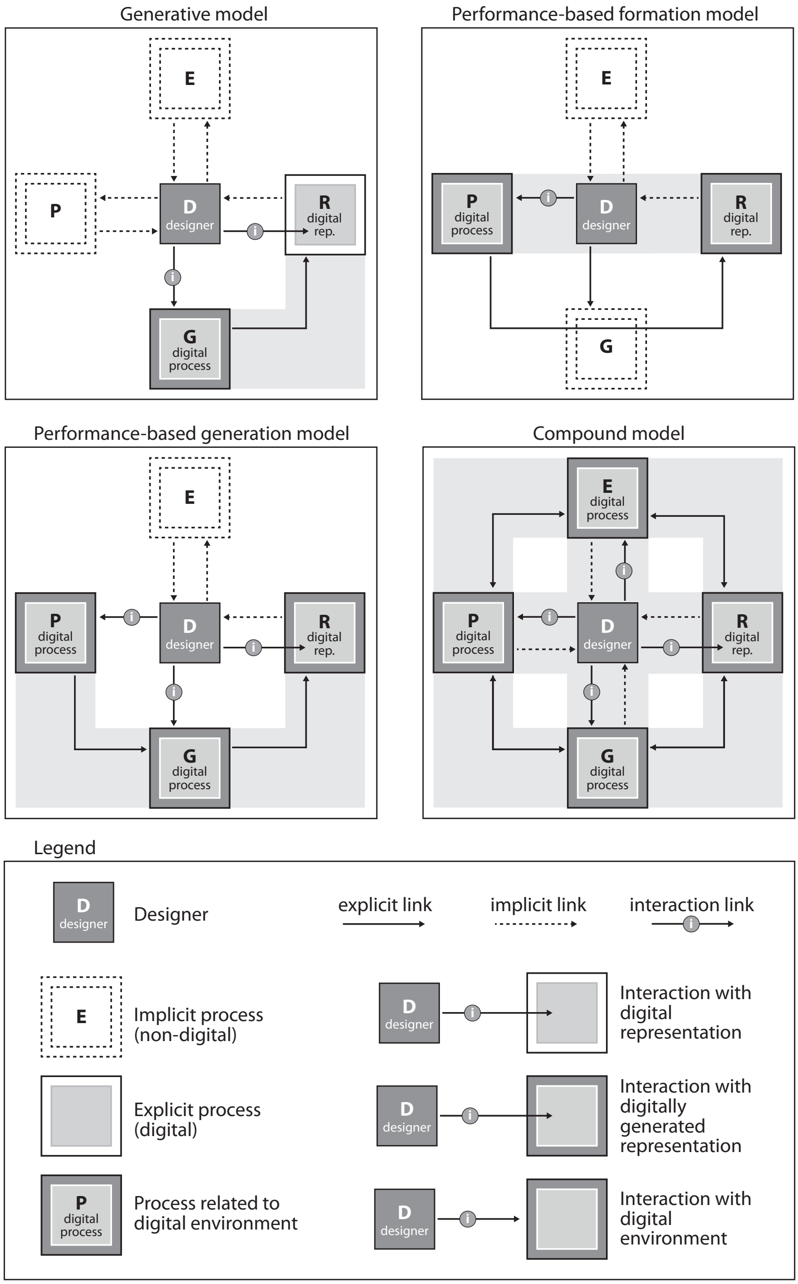


Figure 3.7.
Four classes of digital design models. Each model depicting the relationsship between the designer (D) and four classes of traditional design activities: representation (R), generation (G), evaluation (E), and performance (P).
Models based on (Oxman, 2006), redrawn by Mads Brath Jensen.

The methodological characteristics of Oxman's models allow for a positioning of the PhD project and the methodological approaches towards the establishment of human-material-robot processes. The 'Integrated compound model', in particular, encompass the desired integration of design activities. The compound model represents a class of computational systems that enables the designer to interact with all the defined design activities directly and includes a multi-directional flow of information within the system. When described by Oxman, the 'integrated compound models' represented a class of future digital design media. However, recent work has observed *"…several computational approaches addressing the entire cycle of the generation, evaluation, and selection of design alternatives."* and continues to state that *"…although generation, evaluation and selection correspond to different aspects of the design process, the current focus is to integrate them into common environments to facilitate their interaction*". (Bernal, Haymaker and Eastman, 2015).

In general, digital design systems classified as belonging to any one of Oxman's models, are characterised as complex and integrated design systems and defined specifically by the degree of individual control provided to the designer. As Oxman concludes in her presentation of the digital design models: "*It is supporting complexity that is the mandate of design in the second digital age*" (Oxman, 2006). This also entails that the role of the designer includes both the specialist knowledge needed to build the digital systems, the idea of the designer as a toolmaker as opposed to the designer as a user, and the knowledge to operate such systems. Referring to Oxman's models, the level of direct interaction with the design activities, which, together with the established information flow classifies the five digital design models, requires increasing knowledge of the designer. This might affect the scientific approach of this PhD project, with regards to separating the investigative design studies into two types; on based on the activities of an expert designer and the other on novice designers, and lead to the investigation of human-material-robot design systems belonging to each their category of the design model. While the general aim certainly is to develop and investigate a robot-based digital design system of the 'compound model' class, where interaction with all the modules proposed by Oxman (representation, generation, evaluation, and performance) is possible, the knowledge requirements in the novice-based studies presumably have to be lowered. This implies that the implemented digital design systems likely belongs to the 'Performance-based generation model' or the studies might show that novice students are capable of handling the same system as the expert designer, although interacting with its modules on a lower level, leading to more simple interactions.

The interactions and information flow described through Oxman's design models also depicts distinct views on how the computer, or the CAD software running on it, is utilised. One approach is depicted in the 'traditional CAD model' and the 'Generation-evaluation model', in which the designer is described as interacting with the graphical representation of digital objects. As the name of the second model points out, the designer can also evaluate these digital objects through digital methods. In the other approach, which is deployed in the 'Generative', 'Performance-based, and 'Integrated compound' models, the designer engages directly with the rules, relations, and algorithmic coding of the generation processes and not directly with the form itself. The importance of, and the difference between, these two approaches are clarified by Kostas Terzidis, Professor in Algorithmic Design. According to Terzidis, it is crucial to differentiate between the two terms: computerisation and computation, which he describes in the following way:

> *"While computation is the procedure of calculating, i.e. determining something by mathematical or logical methods, computerisation is the act of entering, processing, or storing information in a computer or a computer system. Computerisation is about automation, mechanisation, digitisation, and conversion. Generally, it involves the digitisation of entities or processes that are preconceived, predetermined, and well defined. In contrast, computation is about the exploration of indeterminate, vague, unclear, and often ill-defined processes; because of its exploratory nature, computation aims at emulating or extending the human intellect. It is about rationalisation, reasoning, logic, algorithm, deduction, induction, extrapolation, exploration, and estimation. In its manifold implications, it involves problem solving, mental structures, cognition, simulation, and rule-based intelligence, to name a few."* (Terzidis, 2006)

Computation and creative exploration

From the clarification offered by Terzidis, it is evident that the procedures associated with computation are vital for investigating design exploration and the cognitive processes related to computational-based problem-solving. Terzidis' emphasis on the exploratory nature of computation is of particular interest to the study of human-material-robot design processes. In seeking to establish design methods that support creative and indeterministic design processes, the study must ensure that the design methods support an explorative approach and that the implementation of computational procedures allow the designer to work with these ill-defined processes. Referring back to Boden's work on the cognitive processes in creativity, one can also state that computational exploration has to extend the exploration of the mental spaces, also referred to as conceptual spaces, in a person's mind.

The concept of the mental space, as related to human cognition, can be compared to the concept of a search-space in computation. A search-space defines all the possible states that a computational solver can pass in the process of seeking a specific solution to a given problem (Boden, 2004). While mental spaces, containing all the human thought-processes, are to a large degree hidden from the persons themselves, computational search-spaces are defined by well-structured constraints and thereby permits precise mapping of the space. While the size of mental spaces is limited by previous experiences, computational search-spaces are restricted by the established constraints. Although the size of search-spaces can expand to the infinite, in practice, searching through all solution of an infinite search-space would literally take forever – making the act of defining, setting up, and adjusting constraints a vital task for the computational designer.

Constraints for design exploration

Computational design tasks involve iterative explorations and redefinitions of the search-spaces, which in the context of computational design can be referred to as the design space. Seeking to identify search-areas with high potential and trimming off irrelevant areas by readjustment, deletion or creation of constraints, becomes a crucial design task. The importance of constraints for design exploration has been discussed by Axel Kilian, in his study of 'Design Exploration through Bidirectional Modeling of Constraints' (Kilian, 2006). Kilian argues that although constraints are generally viewed as limiting factors in design they "…*can help to focus design exploration*" (Kilian, 2006) and suggest that constraints, during a design process, might evolve into design drivers for innovative solutions. Boden also elaborates on constraints and their importance on creative thinking: "*… far from being the antithesis of creativity; constraints on thinking are what make it possible. This is true even for combinatorial creativity, but it applies even more clearly to exploration-based originality."* (Boden, 2004).

The process of finding and applying constraints to a given design problem can be approached from several directions. One approach is analysing the problem for existing constraints, for instance by sampling existing solution to the problem. Another approach is to map the design domain, in which case diagramming the accumulated information can help expose patterns and tendencies leading to the identification of new constraints. The last approach, connected to domains like robotic fabrication, is to specify constraints related to the specific fabrication constraints that apply to the physical realisation of a given design artefact. One of the hypotheses of the PhD project concerns the creative potentials in identifying these robotic-based fabrication constraints and actively exploring their impact on possible design solutions during the early design stages. Referring to Kilian, the constraints potentially identifiable through processes of robotic fabrication and physical realisation of design solutions, could evolve into design drivers and thereby trigger new creative thought processes.

Exploring solutions spaces

Generally, the exploration of design spaces, and their associated set of constraints, belongs to two distinct categories: manual or automated search procedures (or a combination of both). Both procedures have their apparent advantages. One dependent on the manual change of design variables, but featuring a rich opportunity for user intervention in guiding the process. The other relying on automated processes, where utilising genetic algorithms or other optimisation procedures, allow for a structured and goal-oriented search. Depending on the size and complexity of the design space, one search approach might show superior, and another too cumbersome. However, successfully running an automated search algorithm requires an understanding of the underlying theory of computational solvers. In the case of generic solvers, knowing the theory of thermodynamics is essential to understand the search processes of simulated annealing. The same goes for evolutionary algorithms, which requires knowledge about biological principles of mutation, selection and inheritance (Rutten, 2013). For the studies conducted in this PhD project, the intention is to implement existing solvers and investigate their potential role in the decision-making and exploration of performative design systems, which has to negotiate between multiple design criteria (such as environmental performance, material properties, and fabrication constraints). Due to the mentioned knowledge requirements, computational solvers is only implemented and studied in the design studies conducted by the author, and not when involving novice designers.

3.2.2 Creative impact of Computational Design Tools and Processes

Having touched upon the theoretical potentials of computation in architecture and ways in which it can support creative and explorative design processes, it is essential also to examine experiences gained from empirical studies on the influence of using computational design processes.

In a case study performed through participant observation, Robertson and Radcliffe extracted four categories of effects: *enhanced visualisation and communication, circumscribed thinking, bounded ideation, and premature fixation* (Robertson and Radcliffe, 2009). Although the study was conducted more than a decade ago and thereby based on the use of computational design tools applied in practice at that time, some elements of the results are still applicable to current processes of computational design.

For the effects of *enhanced visualisation and communication*, it is especially Robertson and Radcliffe's observations of the negative mental aspects associated with detailed display of CAD models, that is of interest. The "*illusion of completeness*" (Robertson and Radcliffe, 2009) was recognised as discouraging to creative thoughts. With the implementation of robotic fabrication and material experimentation, It is expected that the illusion of completeness is less challenging, as the graphical interaction with a CAD model is replaced by a parallel exploration of the model's generative system, simulated performance, physical realisation, and with physical explorations of potential material effects.

Robertson and Radcliffe's observations showed *circumscribed thinking* to be a serious barrier to the creative process, as it "…pushed design decisions away from what best met the design criteria to what was easiest to generate with the tools available." (Robertson and Radcliffe, 2009). This observation can lead to negative circumscribed thinking, due to reasons like poor functionality of digital tools, lacking knowledge of these tools, unsupportive design processes, or simply due to time pressure. But, it can also foster positive circumscribed thinking, as when the functionality of the digital tool encourages an excessive use of specific generative methods, resulting in design solutions featuring unnecessary complexity. Both types of circumscribed thinking should be presented as significant challenges to be addressed through the proposal of design methods for collaborative human-material-robot processes in architecture. However, when evaluating the proposed design methods, it is essential to appreciate that the planned design studies deliberately features pre-constrained and narrowly defined problem-spaces, where design variables such as material selection, fabrication technology, assembly method, and procedure for human-robot collaboration are predetermined. The circumscriptions of the individual design studies are necessary for ensuring achievable design processes that are feasible within the periods of the PhD project and the university course modules, achievable with the available robot technology, and possible to realise through the development of a bespoke computational framework. Only creating ideas within these methodological and technological boundaries should, due to these restrictions, not be seen as an effect of circumscribed thinking, but as a result of highly focused design explorations. That being said, both types of circumscribed thinking can, of course, appear during the design studies and should be included in the evaluation of the proposed design methods. As in the case of the illusion of completeness, mentioned above, it is the expectation of this thesis, that the parallel explorations and co-evolutionary design processes related to robotic-based design methods can help mitigate the challenges with circumscribed thinking.

According to Robertson and Radcliffe, *bounded ideation* can occur when CAD tools are used continuously and negatively affects the creative potential of the designer (Robertson and Radcliffe, 2009). Bounded ideation refers to the relationship between idea quantity and idea quality within boundaries that impose limits on human cognition (Briggs and Reinig, 2010). The observations by Robertson and Radcliffe suggests that always working in the CAD environment affected idea generation and that *"the best environment for idea generation tended to occur away from computers, in small meetings, characterised by large amounts of sketching and discussion.*" (Robertson and Radcliffe, 2009). Relating these empirical observations to Csikszentmihalyi's theory of creative flow, the mentioned situation could be explained by the challenges faced by the designer (maybe only periodically) being more prominent than the available skills, thereby affecting the intrinsic motivation leading to inhibited idea generation. Seeking to construct and investigate design methods that integrate several different environments for supporting idea generation (computational design, robotic fabrication, manual prototyping, material investigations), the work conducted in this thesis directly seeks to avoid bounded ideation. Robertson and Radcliffe's reflections on the disadvantageous effects of fixation to a single environment for idea generation also emphasise the importance of critically examining how existing idea-generating environments can be embedded in new methods for creative exploration of human-robot design processes.

*Premature fixatio*n was the last phenomenon observed by Robertson and Radcliffe, and it was remarked that: "*…a resistance developed to ideas which would lead to too many changes to the model itself or to its underlying structure. The resistance was present even if these changes would solve numerous problems…"* (Robertson and Radcliffe, 2009). When related to solving design tasks, the time spent creating a design solution can be associated with a perceived cost, including working hours and mental energy. Abandoning, or drastically changing the design concept, or the CAD model, is therefore met with a certain resistance. From a cognitive aspect, the reluctance to explore new possibilities can be a result of human limits of working memory affected by mental processes like *spreading activation*, making it difficult to leave a given trail of thought and switch to a new line of thinking (Briggs and Reinig, 2010). It has been argued that external stimuli can assist in activating new knowledge areas and promote the pursue of new thought patterns and prevent *cognitive inertia*, a condition leading people to create increasingly similar ideas (Briggs and Reinig, 2010). The observations of Robertson and Radcliffe were based on the design of CAD models, in which case, the incorporation of new ideas demands manual re-modelling of digital objects. This process can be a timely affair and, if occurring often, also lead to a decrease in the designer's intrinsic motivation. A key factor for avoiding premature fixation, when related to the use of computational tools, can be the acquisition of a more flexible and transparent approach, to which the use of parametric design environments shows great potential.

3.2.3 Computational Frameworks

In the presentation of 'Computational Design Thinking' (see chapter 3.2.1), it was argued that computation is vital for the investigating of creative design exploration. It was also stated that the generative capabilities of computers demonstrate an ability to support solution-driven processes, and that computational frameworks, through the incorporation of design parameters and constraints, facilitates the generation and evaluation of alternative geometric solutions.

During the last two decades the development of computational design system has greatly influenced the design and realisation of architectural solutions. However, equally important, these technological advances have empowered designers with computational environments that allow for the development and implementation of bespoke design tools.

Building generative algorithms

The research questions put forward in this PhD project are partly based on the emergence of these CAD environments, and the associated potentials of creating and exploring generative algorithms. Utilising these existing digital modelling tools for the development of bespoke algorithms, established through a combination of visual programming and text-based programming, allows for the construction of computational design systems that potentially support the exploration of novel solution spaces.

Currently, there are several CAD environments on the market that support the design and customisation of generative design systems. For the scope of this PhD project, it is decided to focus the development of computational design systems to a single CAD environment, namely the parametric CAD environment comprised by Rhinoceros 3D and the integrated graphical algorithm editor Grasshopper. The choice is based on several factors, including the author's previous experience; the pre-existing integration of the CAD environment in the teaching curriculum at the author's department; the availability of existing tools to facilitate robot programming, simulation of environmental performance, the automated search of solutions fields, and most important the option of programming customised components. Utilising the parametric environment of Rhino & Grasshopper as the application in which to construct and explore a computational framework that supports investigation of human-material-robot design methods, it is essential to understand the creative and cognitive processes attached to this type of design tool.

The choice and application of a specific CAD environment, like the choice of any design tool, analogue or digital, has an effect on the resulting design process and how cognitive challenges, or barriers, are faced by prospective designers. Comparative evaluations of parametric design systems have shown that the cognitive challenges associated with parametric modelling occur at different phases, some uniformly distributed, and some at the earlier or later phases (Aish and Hanna, 2017). At the same time, it is evident that the perceived cognitive challenges differ substantially depending on the modelling task at hand and the aptitude of the user. Based on their comparative evaluations of parametric design systems, Aish and Hanna concluded that: *"the important role of parametric design applications is to present parametric design concepts to designers and for the designers to be able to use these applications to express parametric design thinking."* (Aish and Hanna, 2017).

Together with the strength of visual programming, found in most parametric design applications, designers are afforded with a very flexible design tool in which modelling operations can be revisited and potential changes automatically updated throughout the model; an advantage also referred to as *continuous* flexibility (Davis, Burry and Burry, 2011). This flexibility allows rapid exploration of solutions based on an alternation of design variables, but the flexibility is challenged when new design ideas deviate from the current trajectory, requiring a manual rebuild of the internal relationships. This limitation in generating solutions beyond the preconceived scope of the parametric model can result in a premature reduction in the range of explorable design options (Bernal, Haymaker and Eastman, 2015), and lead to premature fixation, as previously described.

The ability of a parametric model to adapt to new design requirements, through processes of manual rebuilding, is described by Woodbury as *discrete* flexibility (Woodbury, 2010) When dealing with the flexibility of a parametric model it is important not to define flexibility as merely a spectrum, spanning from the less flexible to the more flexible, but as a "*combination of modelling attributes whose measurement is context dependent*" (Davis, Burry and Burry, 2011). In this context, modelling attributes refers to the level of flexibility during the generation of the model, when making required changes, or when identifying where to make changes. According to Davis, Burry and Burry, one of the current limitations on parametric modelling is: "*the designer's ability to generate a flexible parametric model*" (Davis, Burry and Burry, 2011).

Concerning the PhD project, and the design of computational models for supporting human-material-robot design processes, keeping a critical and nuanced approach to parametric flexibility, should be emphasised. Not only during the development of new computational design methods, where increased flexibility are presumed to support creativity but also as a vital aspect in the evaluation of the proposed design methods, where lack of flexibility could increase the probability of creative and cognitive barriers and inhibit design exploration. The actual task of rebuilding or adjusting the scope of a computational model to accommodate new ideas is a challenge for which resolvement relies on technical skills and design experience. The perceived flexibility of a computational framework is therefore likely to differentiate between individual users, affecting the explorative level of the design processes and the quality of the design solutions. This correlation further supports the necessity of a research design that includes design studies with both novice and expert designers. Such studies are expected to aid the process of identifying how computational methods, as an integrated element in a co-creative human-material-robot design process, might influence the creative and cognitive design process.

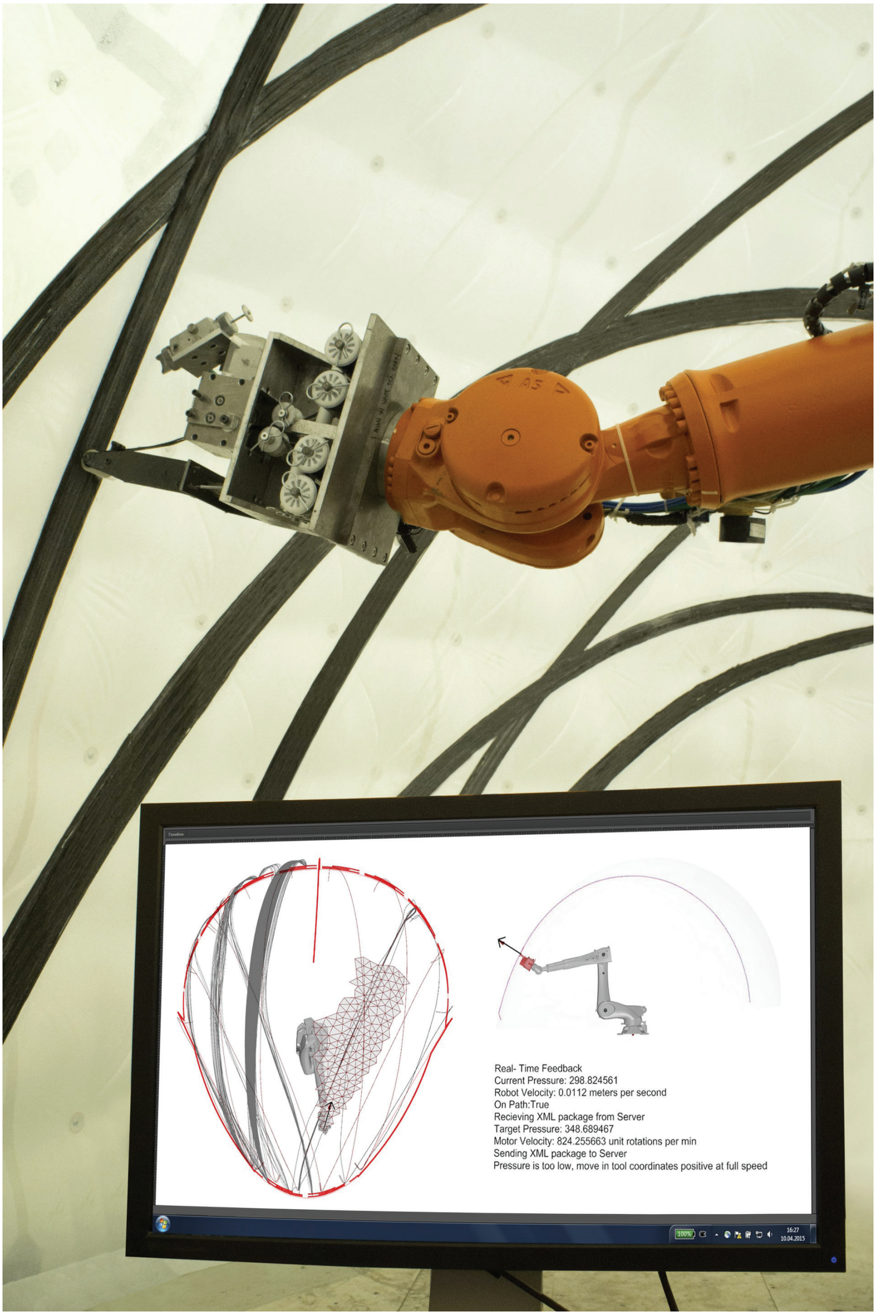


Figure 3.8.
Development process of the ICD/ITKE Research Pavilion 2014-15. The force-sensing robotic arm applies carbon fibers to the inside of an inflated membrane.
Photo by ICD/ITKE, University of Stuttgart.

3.3 Creative Robotic Processes

3.3.1 An Introduction to Robotic Machines

Robots are often seen as the masters of the three D's: the jobs that are dirty, dull and dangerous. The majority of robots are used in dirty environments, performing tedious, repetitive assembly or welding tasks on the factory floors, or cleaning up after nuclear accidents (Murphy, 2019). To understand the motivation for using robots in architecture, one can begin with a general examination of the main reasons for implementing robots.

On a very general level, the main motives for using robots can be divided into four main reasons: "*to* ***replace*** *or substitute for humans, to allow humans to* ***project*** *into a remote environment, to* ***assist****, and to* ***amuse***" (ibid., p. 11). As showcased in the first chapter of this thesis, the field of robotic architecture can be perceived as originating from projects seeking to replace human workers, as seen in the Winery Gantenbein project (Gramazio, Kohler and Willmann, 2014), where an industrial robotic arm replaces human bricklayer. However, it can also be argued that even in the early robotic-based architectural projects, robots did not merely replace humans; they also served to assist architects in exploring new methods for making and assembling architecture. Today, the majority of novel projects in the field of architectural robotics, as we shall see later on, investigates an extensive range of methods to assist craftsmen and designers in both the exploration and fabrication of novel design solutions. The driving force behind many of these robot-based projects is not enhancing the speed or efficiency of existing design and fabrication processes. Instead, it is the exploration and discovery of novel design methods and fabrication processes that support the fusion of human and robotic agency.

The architectural potential of robots can also be examined from the perspective of the major components that make up most robots. With the thesis focused on industrial robotic arms, these components are *effectors,* the arm of the robot enabling it to act on the environment; *perception,* the sensors that allow the robot to sense the environment; *control,* the robots internal processor that computes the inner and outer control of the robot itself; *communications*, how a robotic arm interacts with other robots or a human operator; and *power*, which enables all the previous functions (Murphy, 2019). Within the current field of robotic architecture, research contributions have expanded from robotic fabrication dealing with communication between robotic arms and computational design software and the development of novel and bespoke end-effectors to incorporate perception through the implementation of various sensor technologies. Examples of sensing robots have been mentioned in the Introduction chapter, with references to the use of a force-sensing robotic arm in the ICD/ITKE Research Pavilion of 2014/15 (Doerstelmann, Knippers, Koslowski, *et al.*, 2015a)(see figure 3.8), to robotic weaving and sensing with a depth camera (Brugnaro, Vasey and Menges, 2008), robotic carving with a force-feedback sensor (Brugnaro and Hanna, 2019), as well as robotic sheet forming utilising both a laser distance sensor and a load transducer (Nicholas *et al.*, 2015).

Besides depicting an increasing shift towards the implementation and investigation of sensing and acting robotic fabrication systems, these research projects represent a change in the way robots are treated. In general, robots can be classified and treated as either *tools*, *agents* or *joint cognitive systems* (Murphy, 2019). Treating the robot as a *tool* implies that the robot performs specific tasks, which can vary from simple to highly complex, but without the ability to adapt to contextual changes, like the brick stacking robot used in the Winery Gantenbein. Adopting an agent-based view of robots implies treating the robot as an *agent* that can sense and adapt to new but pre-anticipated situations; this is argued to be the case for the four sensor-enabled robotic projects mentioned above. The latter approach, *joint cognitive systems*, treat the robot as part of a human-machine team and focus on how human and robots "*cooperate and coordinate with each other to accomplish the team goals*" (ibid., p. 21). In this approach, human-robot interactions are merged with artificial intelligence to create "*robots that can be intelligent enough to be good team members*" (ibid., p. 21).

Engaging with Industrial CNC Machines

> *"A designer today uses a fabrication machine as they might have fifty years ago: they convert a design into digital geometry using a CAD program, they then adjust the geometry to correspond to a fabrication process in a CAM program, and then the digital geometry is converted into machine code and sent to CNC machine"* (Gannon, 2018)

In general, industrial CNC machines are based on the same long-established principles of operation. Although they vary in size, function, and freedom of movement (referred to as *degrees of movement* or DoF), they all operate by moving their tool-tips (end-effector) to a given location (often specified as an x,y,z coordinate) with a specific orientation (an a,b,c rotation around the three axes). When at the correct position, they perform their action, which can be anything from gripping, welding, drawing or depositing to drilling, bending, or cutting. So, whether one uses a laser cutting machine that can move in two axes and precisely control the on/off functionality of its laser-emitting end-effector, or one employs an 8-axis multitasking milling and turning machine that can automatically change between multiple machining tools, the control principles are the same. The workflow for using these fabrication machines have remained the same since their invention more than fifty years ago. Today, the procedure for using CNC machinery begins with the conversion of a design idea into digital geometry using CAD software. The digital object is then adjusted in a CAM program, taking into account the limitations and restrictions of the chosen fabrication process. The simulated machining process is then converted into machine code, describing the precise sequence of each consecutive movement of the end-effector and sent to the CNC machine for execution.

While the field of engineering and industrial design has utilised CAD/CAM processes since the mid-1960s, particularly for the development and fabrication of cars and aeroplanes, digital fabrication in architecture, on the other hand, did not emerge until around 25 years ago (Dunn, 2012). The adaptation of CAD programs from the aerospace industry into architecture, as seen in the design and construction of the iconic Disney Concert Hall by Gehry & Associates, provided an impetus for further technological developments. Thereby gradually permitting architectural practitioners and design students accessibility of digital tools and CNC machinery. In the last two decades, these industrial fabrication machines have afforded architecture with precision, endurance, strength and speed - successfully bridging the digital and the analogue world. However, fabrication machines also pose limitations, such as flexibility and adaptability. Most industrial CNC machines are very specialised towards a specific fabrication process, requiring very controlled environments, for reasons of safety often wholly sealed off from the outside world, and can only process a narrow range of pre-calibrated materials.

Like most CNC machines, industrial robotic arms have emerged from the enclosed and controlled environment of the industrial assembly line. As described in the Introduction chapter, robotic arms distinguish from standard industrial CNC machines. They are not built for a single purpose only but can be equipped with various end-effectors/tools. Combined with the ability to move and orient to a given location in real space, these flexible and adaptable robots are capable of performing an infinite number of tasks – facilitating creative investigations of a diverse range of fabrication processes and material explorations.

Robotic Arms – The Basics

To understand how robotic arms work and why the field of architecture has shown an increased interest in this technology during the last decade, a closer look at the technical properties of these multifunctional machines is needed.

In general terms, an industrial robotic arm can be divided into the mechanical construction of the physical robotic arm and the digital interface from which the robot is controlled. On the physical side, a robotic arm typically consists of seven metal segments connected by six rotary joints. Each joint is controlled by a stepper motor, allowing precise movement of the robot's end-effector (see figure 3.9). The movement and position/orientation of the robot end-effector is generally described through either the rotational value of each joint (ex. j1, j2, j3, j4, j5, j6) or by the position and orientation in the cartesian space (ex. x, y, z, a, b, c). Although the mechanical aspects of robotic arms have been exposed to continuous research and development since its introduction on the industrial assembly lines - leading to faster, stronger, cheaper and more precise machines – the underlying mechanical concept has not changed.

Since the development of the first robotic arms, interfacing between human and robot has been carried out through handheld control units often referred to as teach pendants. By facilitating a manual movement of all axis, the robot can be "jogged" to adjust the position or be sent to a specific position by typing in coordinates. The development of teach pendants has progressed rapidly during the last decade. This advancement is especially evident in the intuitive touchscreen tablets from Universal Robots, allowing non-experienced users to operate their collaborative robots guided by 3D visualisation and an easy-to-use graphical interface (UR, 2020). For solving

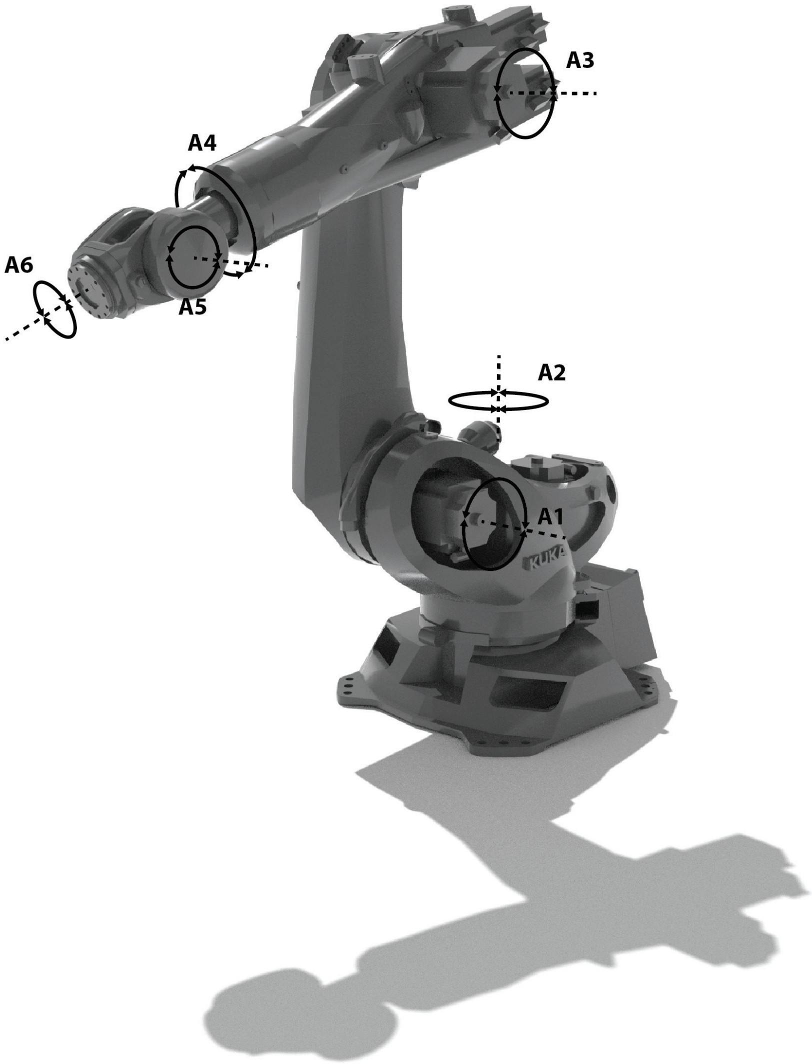


Figure 3.9.
6-axis industrial robotic arm showcasing the degrees of freeom (dof) enabled by the rotary joints (A1-A6).
Illustration by Mads Brath Jensen.

more complex tasks, involving numerous movements and I/O communication with peripheral devices, such as grippers or sensors, the use of computers with robot-specific interface software is often needed. These self-contained computer programs are often supplied by the manufacturer of the robotic arms and allow for the writing, simulation and debugging of robot programs and thereby supplies the user with access to all the functionalities of the specific robot at disposal. Although these softwares are often stand-alone programs, which require a translation and re-configuration of CAD-based design geometry into information suited for generating and simulating robotic positions, they have formed the standard approach for interacting with robot arms.

Within the last decade, the creation of new interfaces, developed from within the creative industry itself, has facilitated more intuitive processes for the definition and simulation of robotic movements (Braumann and Brell-cokcan, 2015). Based on visual programming environments, such as Grasshopper and Dynamo, a range of different robot-oriented add-ons, including HAL (Schwartz, 2013), KUKAprc (Brell-Çokcan and Braumann, 2011), Taco ABB (Frank, Wang and Sheng, 2015), and Robots (Visose, 2016), have made communication with robots accessible to non-experts and offered easier workflows for simulating and controlling a wide range of robot brands. By applying these robot-oriented tools, control of a robot's movements is simplified to the definition of planes in the digital CAD environment, thereby specifying the desired position and orientation of the end effector, in both the digital and physical space synchronously, and choosing the type of interpolation (ex. linear or point-to-point movement) to be made between each position. Kinematic equations for calculating the positions of the robot's joints are solved within the parametric robot components, and robot programs (containing executable robot code) are automatically compiled and can be assessed through visual simulation in the CAD environment. In combination with the computational design environment facilitated by Rhino and Grasshopper, an extension with robot-oriented software add-ons enables the configuration of a computational design workflow. This workflow supports continuous creative exploration between the geometric modelling of a design object, its alignment with and adjustments to fabrication requirements, and its compatibility with robotic fabrication studied through visual simulations. These three distinct processes can be grouped into their respective models: the Design Model, the Fabrication-informed Model and the Robot Simulation Model, as visualised in figure 3.10. The combination of these design models/processes within a collective computational framework has the potential to facilitate an integrated computational design process where intentions and knowledge related to both design and fabrication aspect can be accumulated and re-distributed within the framework.

With the advent of robot-specific interface software, as described above, the potential for creative design processes that combine computational design processes, as previously described in section 3.2, with robotic fabrication processes is now feasible seen from a technical side. By utilising these software interfaces, creative human-robot design processes can be established, allowing design exploration and fabrication to be treated as integral parts of a human-robot co-designing process. An

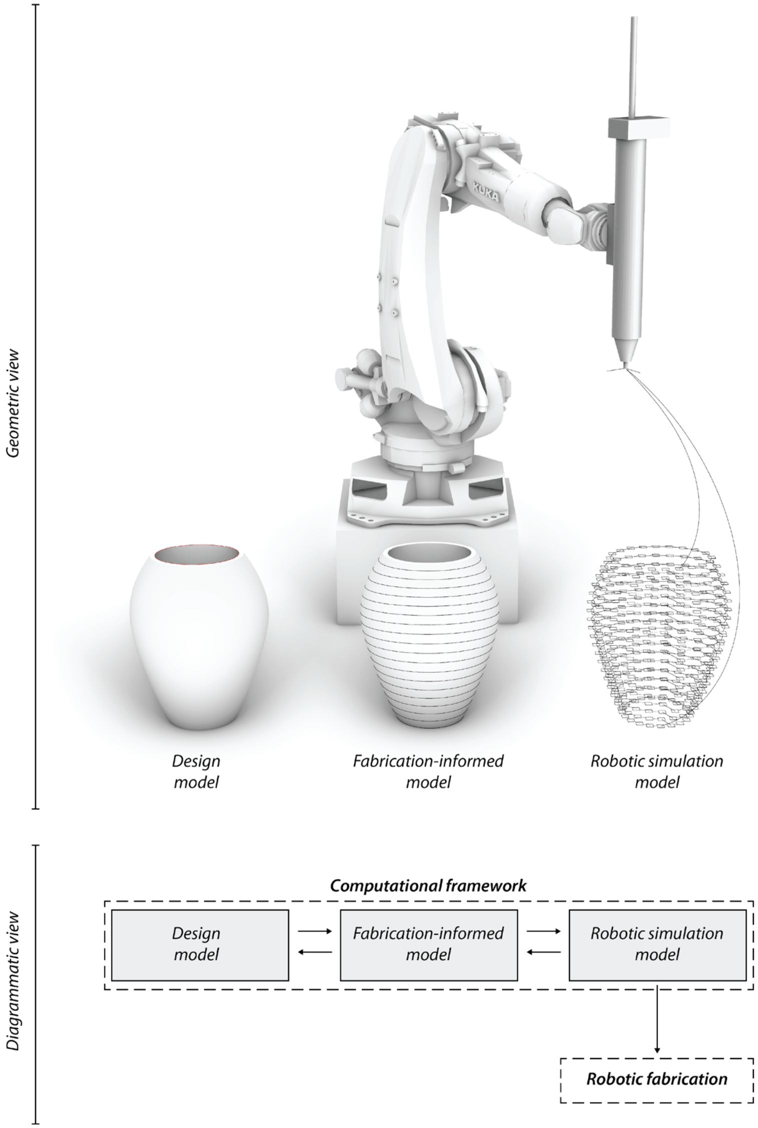


Figure 3.10.
The underlying models that constitute a computational design workflow for simulating and controlling robotic fabrication processes. A parametric framework for robotic fabrication can consists of several distinct processes. These sub-processes can be grouped into the respective models suggested here, namely a design model, a fabrication-informed model, and a robot simulation model.
Diagram by Mads Brath Jensen.

important aspect for further clarification is the existing methods and technologies for communicating with robots - and for the robots to communicate back.

Creative Robotic Workflows

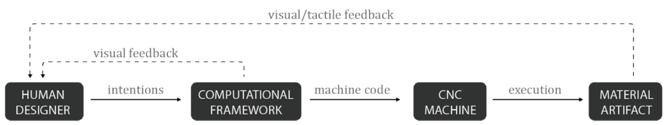
As mentioned in the Introduction chapter, the advent of robot-oriented add-ons for parametric CAD software is one of the leading technological developments that inspired the theme of this PhD thesis. Of specific interest is the potential found in blurring the boundaries between the design activities traditionally assigned to the human designer and the fabrication activities allocated to the robotic system. In exploring the potential of integrated human-robot design processes, two distinct strategies for transferring design-specific information and intention between human and robot are of interest; *offline programming* and *direct robot control.*

Since the arrival of robotic arms, the standard method for programming and control has been offline programming. The workflow associated with offline programming consists of two distinct processes, the design of a machine task and the subsequent execution of this task by a specific machine. Within this process, the *program*, a text file containing a procedural description of machine instructions (also referred to as machine code), serves as the fundamental and only form of communication between human and machine. This linear workflow accounts for the traditional approach towards most CNC-based fabrication in the manufacturing industry. Similarly, this workflow can be associated with the more creative processes of rapid prototyping (milling, laser cutting, 3D printing, to name the most popular).

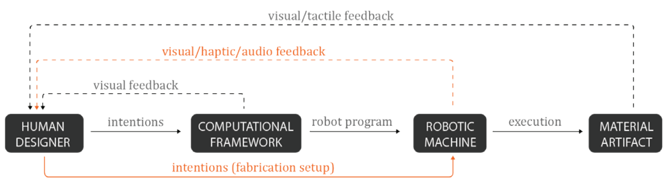
3.3.2 Robotic Fabrication

In the workflow established by offline programming, the *program* itself becomes a "*vessel for the transfer of information and intention*" (García del Castillo Y López, 2019) and requires that all decision-making occurs before the subsequent execution of the program. The model thereby demands a high level of experience and fore-sight to anticipate the scenario that will play out during the robot's execution of the program. When seeking to establish collaborative processes of human-robot design exploration, the unidirectional transfer of data and design intention embedded in the paradigm of offline programming does indeed pose a challenge. Without information feedback, the robotic execution is restricted to a deterministic process without the option of introducing additional decision-making. Therefore, offline programming is best suited for design and fabrication processes that involve highly controlled and predictable environments. A diagrammatic representation of the transfer of information and intention within offline programming can be seen in the visualisation of the "Rapid Prototyping" workflow in figure 3.11. In this diagram, the four design agents (the human designer, the computational framework, the CNC machine, and the material artefact) are connected through an information flow made up of both linear flows and iterative feedback loops. Although the transfer of information between the human designer and the computational framework can support a highly iterative process, in which visual feedback drives the generation and exploration of new design solutions, the subsequent fabrication process remains largely predetermined. From

Rapid Prototyping
(offline programming)



Robotic Fabrication
(offline programming)



Self-regulatory Robotic Fabrication
(offline programming)

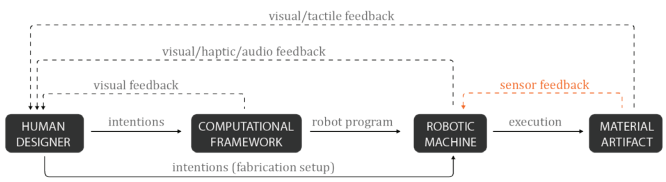


Figure 3.11.
The design and information workflows associated with Rapid Prototyping, Robotic Fabrication, and Self-regulatory Robotic Fabrication.
Diagram by Mads Brath Jensen.

the fabrication process, be it laser cutting of planar wood elements or 3D printing of plastic objects, only evaluation of the final material artefact serves as feedback to the designer's creative process.

In advocating for a more interactive approach towards robotic-based design exploration, it is argued that the offline paradigm "*widens the traditional divide between thinking and doing"* and that it "*pushes the programmer away from the machine*" (García del Castillo Y López, 2019). Although there is much to gain by implementing a more interactive approach, through the integration of sensor-based feedback and the exchange of data between all design agents, the creative potential of offline programming should still be acknowledged. By integrating simulation and control of robotic arms within a parametric design workflow, the above-mentioned robot-oriented add-ons have enabled an offline programming workflow that allows architects to re-connect with material making and explore novel processes for robotic fabrication and assembly. Examples of the creative potentials supported by offline programming workflows can be found in several robot-driven architectural research projects. Among others, the initial explorations of robotic brick-stacking showcased through the robotic fabrication of the previously mentioned Gantenbein Vineyard Façade (Gramazio, Kohler and Willmann, 2014); as well as their subsequent work, exploring robotic strategies for the assembly of complex wood structures, spatial wire cutting, metal folding, and more. In completing several research pavilions, the work conducted by the ICD/ITKE institutes at the University of Stuttgart also showcases this re-connection with material making. In exploring new typologies for bio-inspired robotic constructions, the two institutes developed novel integrative processes of design computation, material performance and robotic fabrication; showcased through the filament winding methods in the ICD/ITKE Research Pavilion 2012 and 2013/14 (Doerstelmann, Knippers, Menges, *et al.*, 2015; Knippers *et al.*, 2015). Similar integration and exploration of material making through robotic fabrication processes can be seen in the work of Wes McGee, associate professor and the director of the Fabrication and Robotics Lab at the University of Michigan Taubman College of Architecture and Urban Planning, and his investigations of both robotic manufacturing of thermoplastic elastomers for tensile surfaces (McGee *et al.*, 2017) and robotic needle felting (McGee, Ng and Peller, 2019). In both projects, utilisation of robotic processes allows for both high precision and local differentiation of material properties, thereby providing the architect with high control of the architectural object's performative capabilities. Referring to the visualisation of the "Robotic Fabrication" workflow in figure 3.11, the main addition setting this approach aside from the more traditional use of rapid prototyping machines is the engagement with, and customisation of, the robotic fabrication setup and the bespoke material processes it enables.

To a great extent, the novelty of all the projects mentioned above originates from their parallel exploration of custom-engineered end effectors and creative investigation of novel material performances and bespoke fabrication processes. In the creative design processes facilitated by such robotic fabrication workflows, the designer gains the option of extracting valuable feedback, not just from the fabricated material artefact but from the potentials discovered within the processes of material making. Additional examples of research investigating this material and fabrication driven workflow includes hot-knife carving processes for mass-customisable formwork (Clifford *et al.*, 2014). Exploration of robotically-actuated multi-material extrusion processes (van Zak *et al.*, 2018). Exploration of new typologies of architectural form through the integration of rocks, strings, and robotics (coined Rock Printing) (Aejmelaeus-Lindström *et al.*, 2016), to name a few.

The creative benefits that reside in the implementation and investigation of these material-making processes can be ascribed to the parallel exploration of bespoke tools for making, ranging from fit-for-purpose to all-purpose tools (as described in chapter 3.1.2), and the material properties that emerge from these physical processes.

3.3.3 Self-regulatory Robotic Fabrication

In reviewing research projects disseminated through one of the key conferences in the field of robot-based architecture, the biannual RobArch Conference (initiated in 2012) (Brell-Çokcan and Braumann, 2013), multiple research projects showcase material processes in which offline programming has been an integrative aspect of the creative design exploration. These research projects range from an exploration of completely deterministic processes of robotic making, such as the individual folding of tabs in a custom metal façade system by King and Grinham (King and Grinham, 2013), fabrication of band sawn bands from irregular wood flitches by Johns and Foley (Jeffers, 2016), folding and bending of sheet metal by Saunders and Epps (Saunders and Epps, 2016) and hot-blade cutting of EPS foam blocks by Søndergaard et al. (Søndergaard *et al.*, 2016). To projects that are more sensitive to material variations and environmental uncertainties, such as the piling of wood sticks by Dörfler et al. and Jeffers (Dörfler, Rist and Rust, 2013; Jeffers, 2016), and the sewing of wooden shells by Alvarez et al. (Alvarez *et al.*, 2019). In the latter of the two approaches, more robust processes are achievable. The robotic system takes advantage of sensor data and implements self-regulatory procedures that allow for re-calibration of the robotic fabrication sequence. These sensor-enabled approaches can be grouped and labelled as “Self-Regulatory Robotic Fabrication” workflows, as seen in figure 3.11. Although the robotic processes still act within an offline programming paradigm, where all robotic actions are anticipated before the initial execution of the fabrication process, these sensor-enabled strategies allow for more adaptive fabrication processes in which material variations and inaccuracies can be resolved. It is essential to notice that within this self-regulatory workflow, the feedback acquired from sensory devices feeds back into the robot program. In most cases, this triggers a pre-established *if-statement* within the machine code, initiating a series of corrective actions to be executed by the robotic arm. In other words, feedback from the sensory device does not initiate a re-writing of the robot program. It only triggers a predefined loop inside the code and thereby does not alter or update the remaining part of the fabrication processes – the robot only “seeks” to fabricate the material artefact predetermined by the designer. Additional examples of research within this sensor-enabled and to a high degree automated workflow includes the fibre placement methods developed for the ICD/ITKE Research Pavilion 2014/15 (Doerstelmann, Knippers, Koslowski, *et al.*, 2015b) and large-scale 3D printing of insulative formwork for castable structures (Keating *et al.*, 2014).

3.3.4 Adaptive Robotic Fabrication

In the self-regulatory approach to robotic fabrication, inaccuracies, related to either uncontrollable material properties or unforeseen changes in the physical context, are amended through a sequence of corrective actions by the sensor-enabled robot. If successful, the geometric output resulting from these self-regulatory actions will stand as a direct physical representation of the desired design object - precisely as intended and prescribed by the designer. Whereas the self-regulatory workflow reacts to errors by triggering a fabrication process, the workflow associated with Adaptive Robotic Fabrication allows detected errors to trigger a conditional design response (Vasey, Maxwell and Pigram, 2014). As visualised in the “Adaptive Robotic Fabrication” workflow in figure 3.12, sensor input is fed back into the Computational Framework, where it has the potential of informing the computational design system about the current state of the material system, thereby allowing for an adaptation of the design outcome. This adaptive process enables a new design approach where the focus shifts away from the static geometrical description and subsequent making of a predetermined and geometrically described design. Instead, design intent is stored within relational design frameworks with the potential of defining both design and fabrication-based responses to errors detected during the process of robotic based material making (ibid.).

An example of research inquiry into the field of adaptive robotic fabrication can be seen in recent work by Vasey, Maxwell and Pigram, in which they propose a strategy for Adaptive Part Variation. In this strategy, “*the real-time redefinition and fabrication of parts occur during the actual process of assembly, thereby allowing detected errors to trigger a conditional design response.”* (ibid.). Through a case study in which steel rods are manipulated through robotic-based cold bending, the authors investigate a fabrication process in which the bending, mounting, and welding together of metal rods are subsequentially scanned to determine the accurate location of consecutive rod elements within a given space. By feeding the sensor data back into the computational design system, a real-time redefinition of the following rod elements was achieved, allowing for automated interactions between design and fabrication.

Another project utilising adaptive fabrication strategies is the Airforming project by Schumann and Johns (Schumann and Johns, 2019). In this project, a robotic arm equipped with a heat gun exposes polystyrene plates to an iterative and incremental process of selective regional heating. The heating process is followed by a scanning process of the resulting surface, conducted by a second robotic arm equipped with a Kinect sensor and a thermal camera. The point cloud from the scanning procedure is fed back into the computational framework, where it is compared to a predefined goal mesh. Based on this analysis procedure, a new target point and an adjusted

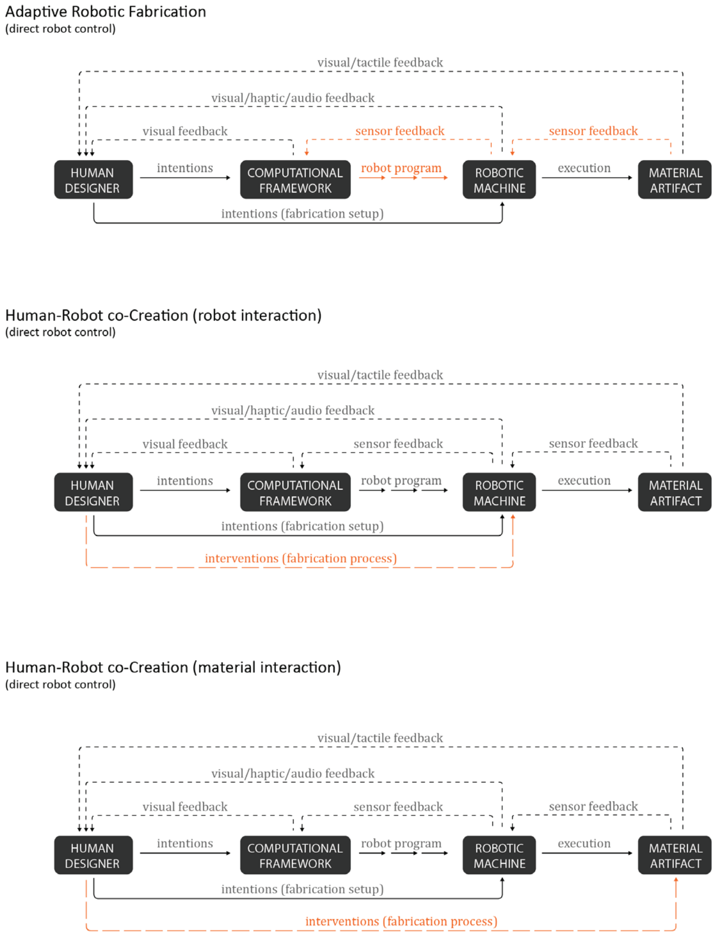


Figure 3.12.
The design and information workflows associated with Adaptive Robotic Fabrication, and Human-Robot co-Creation (in which human-robot interaction occurs either directly with the physical robot or through the material artifact).
Diagram by Mads Brath Jensen.

spiral motion are selected and transmitted to the robotic arm – initiating the next air-forming stage. This iterative process concludes when the shape of the scanned mesh reaches within a given proximity of the goal mesh.

Although both of the two reference projects described above utilise an adaptive robotic fabrication workflow, a difference in the integration and employment of the adaptive processes can be discerned. In the Airforming project, feedback concerning the current state of the material artefact informs the computational framework, initiating the computation of a new robotic fabrication sequence that allows the fabrication process to adapt and reach a predetermined geometrically-described end goal. In other words, the feedback triggers a fabrication response. In the Adaptive Part Variation project, sensor-based information gathered from the material artefact is also fed back into the computational framework. However, in this adaptive setup, data is used to adapt the shape of the following rods through adjustments of their bending radius. The material feedback thereby triggers a design response. The key difference between the two adaptive strategies resides in how the sensor-based feedback connects with the computational framework. As previously mentioned and illustrated in figure 3.10, the computational framework can consist of several distinct computational models. Feedback from the robotic fabrication process can be integrated within each of these models. In the Airforming project, fabrication feedback connects with the computational model that simulates and controls robotic execution, allowing the computational framework to respond through adjustments to the robotic fabrication process. In contrast, the Adaptive Part Variation project feeds sensor data back into the computational design model to trigger modifications of the design geometry, which subsequentially calls for adjustments to the robotic fabrication process.

The strategy for connecting sensor feedback to selected models within the overall computational framework determines both the type and the level of potential responses – directly affecting the adaptability of the robotic fabrication setup and the design processes it affords. This correlation is important to acknowledge as it influences the level of determinacy afforded by the adaptive fabrication setup and, thereby, the potential impact on the creative aspects of the design process. As in the case of the Airforming project, using sensor data to directly inform and modify ongoing fabrication processes, without allowing changes to update or affect the predetermined geometric model, leaves very little room for divergence. Creative stimuli gained from observing the robotic fabrication process most likely derives from unforeseen steps in the fabrication process and their influence on the state and performance of the final object. This fabrication- and material-based feedback can potentially trigger new creative insights and inform subsequent design iterations, thereby supporting the creative design process. If, as seen in the Adaptive Part Variation project, sensor data is connected to the computational design system and used to re-inform the generation of new or modified design geometries, creative insights might occur. Not just from unexpected actions/effects observed during the fabrication process but also from the fabrication of unforeseen design objects. Regarding the creative process, this entails a shift from working with a robot that can showcase unanticipated behaviour in ***how*** it fabricates to working with a robot that might change ***what*** it fabricates.

The above discussion has been based on only two reference projects to outline the strategic differences within the workflow associated with adaptive robotic fabrication. However, a large quantity of significant work has been carried out to investigate the potential design and fabrication advantages of adopting an adaptive approach to robotic fabrication. Novel work includes the exploration of sensor feedback in parametric design processes, as seen in the work of Dubor et al.. In their work, they propose an *iterative workflow* for embedding sensor feedback within the parametric design software and a *behavioral workflow,* where the response to sensor feedback is achieved by integrating fabrication logic within the robot script (KRL script), thereby circumventing the parametric software and achieving almost real-time robotic response (Dubor *et al.*, 2016). Restrictions associated with traditional robot control languages, such as the KRL for Kuka robots and the limitations of using digital input/output from the robot controller, were identified by Dubor et al. as having a negative impact on the creative processes for both experienced and inexperienced users.

From a material perspective, the Robotic Softness project by Brugnaro et al. (Brugnaro *et al.*, 2016) highlights the potential of adaptive robotic fabrication processes. Based on a series of integrated sensor-actuator feedback loops, the robotic based system enables an iterative weaving of rattan sticks. This process would have been infeasible with a standard linear fabrication process as each step in the ongoing fabrication process deforms and reshapes the flexible structure. As this robotic construction process deviates from predetermined design outputs, Brugnaro et al. conclude that their work suggests "*an alternative approach for production where the design process is not centered on realising a predefined solution, but instead embraces explorative and experimental processes*" (ibid.). The project thereby points towards robotic fabrication as a non-deterministic and creative process.

In more construction-oriented projects, like the robotic bricklaying by Elashry and Glynn (Elashry and Glynn, 2014), adaptive sensor-based workflows support automation-driven construction processes. Here continuous sensor feedback is used for error monitoring of mortar layers and compensation of brick placements. Such projects restrict the creative design process to occur before fabrication - with an end goal of deliberately excluding the designer from the robotic fabrication process. Although this last project focus on automation procedures that excludes human participation and the potential of creative feedback, novel approaches to robotic fabrication are demonstrating an increased interest in the creative potentials residing within human-robot collaboration. More precisely, within the creative processes of human-robot co-creation.

3.3.5 Human-Robot co-Creation

As delineated by the advancements in the above-mentioned studies, the field of robotic fabrication is experiencing a movement towards less deterministic and more open and explorative processes of material making. Several aspects have supported this shift, among these the advancements of new computational workflows that supports the integration of sensor feedback and allows for both robot simulation and direct robot control. The implementation of various sensor technologies, such as laser distance sensors, image and depth cameras, touch sensors, and force torque sensors, has enabled a registration of physical properties and facilitated adaptation to external stimuli. Although the precision of both robotic sensing and actuating devices often surpasses that of humans, adaptive robotics are still limited by the range of sensors and by the time expenditure of computational post-processing, analysis, and comparison of collected sensor data. Humans however are very adept at working in highly dynamic and unstructured environments, acting on a combination of a multitude of sensory inputs quickly filtered, processes and compared to a vast knowledge bank of prior experiences.

Recently, the creative potential of human-robot collaboration has encouraged novel research inquiries into the exploration of new workflows for human-robot co-creation and the creative design processes they enable. Prior to an examination of relevant research inquiries into human-robot co-creation methods, a clarification of the two terms: *co-fabrication* and *co-creation*, is appropriate. Although the two terms are often used at random and both entail levels of human-robot collaboration, this dissertation use the term co-fabrication to refer to processes in which human and robot are collaborating to fabricate a predetermined material artifact, while the term co-creation will be used to describe an act of collective creativity (Sanders and Stappers, 2008) in which human and robot engage in collaborative design exploration. While the methods and activities associated with both terms are certainly capable of supporting a creative design process, differences in flexibility and adaptivity between the two approaches results in different strategies for the integration of human-based and sensor-driven design feedback. In co-fabrication all design-relevant feedback (acquired by human senses or through sensory devices) is collected during the fabrication process, but, due to the pre-determined nature of the linear fabrication process, this information is not used to re-informing the design process until after the completion of the fabrication process. In contrast, the more flexible and less deterministic strategy of co-creation allows both human and robotic reactions to affect and adjust the ongoing process of material making – allowing material and fabrication feedback to initiate design responses in real-time and without restarting the fabrication process (Braumann, Stumm and Brell-Çokcan, 2018).

In figure 3.12, the workflow associated with *human-robot co-creation* is presented through two independent diagrams, each visualising a distinct interaction scenario identified from existing work within the field of robotic architecture. The difference between the two diagrams, and the workflows they represent, lies in the interaction strategy and the methods in which the human design agent communicates and passes on design intent. Following one strategy, the ongoing fabrication process can be made open for human interventions through direct interactions with the robotic agent. As showcased in the following referenced work, human-robot interactions can occur through haptic interactions, speech, and body language. In contrast, human-material interactions can be based on physical modifications of the material object(s) or through the introduction of additional material elements.

As previously mentioned, research into Adaptive Fabrication workflows took advantage of new methods and software solutions to transition from offline programming and file-to-factory workflows to more direct control of robotic actions through sensor-feedback and real-time communication. These methods for direct robot control can also support the integration of human decision-making and human-robot interactions during ongoing processes of material-based co-creation. Notable cases of such research endeavours feature projects in which human agents interact with robotic arms through digital interfaces. One such case is the AROSU project. In this project, a computational interface (utilising mxAutomation for KUKA-prc) allows stonemasons to exploit their craft knowledge through direct interaction with the fabrication parameters of an ongoing robotic stone-structuring process (Braumann, Stumm and Brell-Çokcan, 2018). The potential in human interaction during ongoing robotic fabrication processes is also explored in recent work by Peng et al., where a 3D printing process can be re-informed on the go by a designer interacting with an augmented digital representation through an AR headset and controller (Peng *et al.*, 2018). Similar work with augmented reality interfaces can be seen in the *Interactive Milling* project by Johns (Johns, 2014). The utilisation of human guidance within real-time human-robot co-fabrication can also be seen in the construction of the "Tight Squeeze" pavilion, a large-scale structure made out of 2x4 wooden studs (García del Castillo y López, 2019). In this exploration of interactive robotic construction systems, a human supervisor can guide and tweak the pick-and-place movements of two robotic arms. By giving instructions via a video controller, the human supervisor can thereby avoid object collisions during the ongoing robotic fabrication process, eliminating the need for pre-calculating an otherwise complex set of collision-avoiding robot motions.

From the perspective of co-creation and creativity, it is essential to notice the role and influence of the human agent in these human-guided robot fabrication processes. In the stone-structuring project, decisions made by the stonemason directly influence the design of the final stone surface, allowing material knowledge and creative intent to guide the fabrication process. In making the wood pavilion, the human supervisor can influence the robotic movement between predetermined positions for picking up and placing wood elements. Consequently, the human agent's decision-making cannot influence the placement of wood elements or the design of the final pavilion – thereby removing the human supervisor from the creative design process. For the future investigations of design methods for human-robot co-creation, it is essential to propose new workflows that enable human decision-making to influence the execution and trajectory of ongoing material making processes. Such workflows should allow the emergence of human design intention to affect the design of the fabricated object.

Another essential aspect identified in both projects is that human-robot interaction occurs through a device external to the making process. These external devices, respectively a computer software interface and a video game controller, physically distance the human agent from the making process - hindering direct physical interaction and tactile feedback. Despite the risk of distancing the human user, both projects showcase how intermediary interaction layers support a skill-based splitting of tasks. Both projects allow the human user to utilise accumulated craft knowledge and advanced spatial understanding while letting the robot manage and execute highly precise movements. Based on both projects, it can be argued that the collective and individual-based, human-robot skill-set is essential for the successful execution of the specific material making processes. A focus on the augmentation of human and robot skills is further supported by the work of Vasey et al. In connection with their work on collaborative human-robot constructions, they state that:

> *"The separation of tasks within the production pipeline can be specialised according to ability: a robot's precision can be augmented by the fine motor control and cognitive ability of the human, and the monitoring of the process and feedback enabled through user interfaces allows the seamless trade-off of tasks between human and machine." (Vasey* et al.*, 2016)*

Vasey et al. has successfully constructed a robotic fabrication process in which the human collaborator (in this case, random visitors at an exhibition), guided by in-time instructions displayed on an Apple Watch, utilises inherent manual dexterity to load and fasten bamboo sticks on a custom end effector. After that, the robot performs precise movements to accurately wind filament onto the bamboo stick, incrementally depositing material and building unique modules for a larger assembly. The dexterity and cognitive abilities of the human participants thereby augmenting the precision and repeatability of the robot movements (Reinhardt, 2019). However, due to the predetermined process of robotic filament-winding, the human user is not 'allowed' to propose new input or alter the design intentions, thereby not participating in a creative process. In this case, humans and robots participate in a collaborative process involving co-fabrication and not in one concerned with co-creation.

In recent years, considerable work has been invested in exploring the potentials and limitations of co-creative human-robot design processes. Grounded in a fundamental desire to "*reconsider the role of the human designer in the face of increasingly complex automation in fabrication"* (Johns, Kilian and Foley, 2014), a design and fabrication process integrating both human and robot within an interactive cyclical workflow was constructed (Johns, 2014). In this *Mixed Reality Modeling* project, a robot-mounted heat gun melts away material from a block of wax. At the same time, a 3D scanner and an RGB camera, also mounted on the robot, captures the state/shape of the wax object and the placement of physical blocks implemented to indicate structural load forces. During the iterative process, the robot heats and melts away wax based on a topological optimisation routine. During this process, the human can intervene at any point by manually changing the load conditions, indicating areas to melt by colouring specific areas of the wax, or physically modifying the wax (Johns, Kilian and Foley, 2014). The results of actions performed by the human can be sensed and reacted upon by the robot – and vice versa. The project thereby allows spontaneous decision making to influence the ongoing robot fabrication process, enabling adaptation to new design intentions. The workflow established in the *Mixed Reality Modeling* project allows the human designer to intervene in an ongoing fabrication process and influence the configuration of the completed material artefact. This indeterministic workflow can be recognised as supporting human-robot co-creation by affording direct interaction with a material artefact, as visualised in figure 3.12.

An investigation of similar design methods for human-robot collaboration is presented in the *MockUp Method* (Pazik, 2019), where the material artefact acts as the shared interface during design exploration. By introducing a sand mould intended for concrete casting, the research project allows both human and robot to add, subtract, and sculpt the sand. Subsequent 3D scans then allow the computer to construct and update a digital model of the physical design. As in the work conducted by Johns, the shared design criteria in this project is based on structural performance, but due to the sand-based material system, the explorative design process is reversible. It will continue until the designer finds that the current formation fulfils all design requirements. From both the *Mixed Reality Modeling* project and the *MockUp Method,* it is evident that co-creation processes can be attained and that the implementation of sensor feedback, computational optimisation routines, and direct robot control is technologically feasible. The projects also indicate that selecting appropriate material systems and suitable methods for both human- and robot-based material processing is critical for the quality of interactions between human, robot and material.

Based on the research projects discussed in this section on Human-Robot co-Creation, two distinct workflows for human-robot interaction can be identified and categorised as *device-based* and *material-based* interactions. With the advent of more sensitive collaborative robotic arms (co-bots), a third interaction method, categorised as robot-based interaction, has been proposed. In such co-creation processes, the human designer can interact directly with the robotic arm through physical contact. Using the cobot's inbuild force-torque sensors, human contact can be detected and used to enable manual movement of the cobot. Examples of work investigating such interaction scenarios include the DIANA project (Dynamic Interactive Assistance for Novel Applications) and the Twisted Arch Demonstrator (Stumm, Devadass and Brell-Cokcan, 2018). In both projects, haptic robot programming allows the human operator to guide and assist the robot manually. Such direct physical interaction is especially useful in scenarios where the "*digital a priori knowledge does not correspond to the constructional reality*" (ibid. p.8), often occurring in collision events or when sensors values are outside an expected range. Although both projects by Stumm, Devadass and Brell-Cokcan enable direct haptic interaction with a robotic arm, situating the human user within the physical fabrication space, they do not place any transformational authority on the human user. By only allowing the human to assist in the event of an error and not giving the mandate to introduce changes to the robotic fabrication process, the haptic human-robot workflows leave no room for new design intention. The human-robot fabrication process thereby follows a predetermined fabrication strategy in which creativity occurs before the initialisation of the fabrication process. For this reason, the haptic human-robot process should not be considered as supporting human-robot co-creation but instead adheres to the definition of co-fabrication. Due to the collaborative opportunities embedded in haptic interaction workflows, it is conceivable that further investigations into this field can develop new design methods that are less deterministic and capable of supporting both collaborative design exploration and human-robot co-creation.

For the last decade, the field of architectural robotics has witnessed a progressive advancement of both technological and methodological concepts. While the above subsections have sought to trace the development of explorative design methods and workflows that supports human-robot co-creation, this exposition has deliberately focused on research carried out within the context of robotic fabrication and material making processes. However, as the study of creative robotic processes in architecture has revealed an explorative potential in design methods that support interactive processes of human-robot co-creation, a consideration of human-robot interaction (HRI) processes outside the domain of robotic fabrication is appropriate.

3.3.6 Creativity in HRI

The field of HRI is vast and involves "*the study of how humans perceive, react, and engage with robots in a variety of environments*" (Hinwood *et al.*, 2018). With contributions from an extensive range of disciplines, including design, robotics, the social sciences, engineering, and more, the field covers many aspects of human-robot interaction. Limiting the field to scientific advancements dealing with creativity and focusing on research work that uses robotic arms allows for a brief overview of relevant concepts and a discussion of their potential contribution to developing new design methods for human-robot interaction and co-creation. In focusing on the study of creativity in HRI and the potentials in collaborative human-robot task sharing, applicable work can be identified within the arts and humanities. Investigations of collaborative open-ended drawing tasks in which humans and robots physically interact represent an artistic context from which interesting research findings can be uncovered.

Recent work by the multidisciplinary artist Sougwen Chung explores communication between human and machine through collaborative pen drawings (Chung, 2019). By equipping robotic arms with the ability to draw marks, Chung has engaged herself in real-time drawing performances that deliberately forces her to respond and improvise to the unknown mark-makings of the robot. Although Chung incorporates artificial intelligence to allow the robot to learn the artist's drawing styles, the creative drawing process is based on human reactions to a series of robotic inputs that are not re-informed, nor reactive, to the ongoing artistic process. While this limitation can be considered a shortage in the collaboration between humans and robots, it does question the role of shared intentions and placement of control. In Chung's work, the lack of control and the occurrence of unexpected acts by the robot is what drives creativity. While the added existence of functional requirements often constrains architectural design processes, the sharing of both control and intentions could be valuable for human-robot design explorations.

In line with the question of shared intentions and how humans might “read” a robot’s intentions, and the potential changes of these during collaborative processes, Chung has stated that she is “*compelled by the human capacity to anthropomorphise our relationship to machines, particularly to robots*” (AIArtists.org, 2021). The anthropomorphic relationship between humans and robotic arms, defined as humans’ ability to attribute non-human entities (i.e. the robotic arm) with human traits, emotions, and intentions, has also been investigated through collaborative human-robot drawing tasks (Hinwood *et al.*, 2018). Through applied experiments, Hinwood et al. utilised the Wizard of Oz (WOZ) experimental design methodology, a control method that allows a human operator to control a robot’s behaviour in real-time (ibid.) to give a robotic arm an autonomous and social appearance. To hint or prompt the human participant to complete a desired action, the project created a set of pre-programmed animated movements to be initiated during the collaborative drawing task. The animated movements were separated into two groups: state commands, used when the robot was to behave in a waiting manner (including motions/poses for “nodding”, “observing”, and “withdrawn”), and action commands, used when the robot needed to interact and communicate non-verbally with the participant (including motions for “prompt pen pick-up”, “encourage to draw”, “encourage to sign”, and more) (ibid.). The results of the experiments conducted with participants are not yet published. However, establishing an anthropomorphic relationship for non-verbal communication between human and robot constitutes a fascinating concept for dealing with shared design intention, robot-based guiding of human actions, and robot-based communication of suggested design/fabrication alternatives. Understanding robot intentions through gesture-based communication also holds the potential for reducing the need for screen-based communication allowing for more direct and inclusive interaction and communication with the robotic co-creator and the material system in use.

The ability for robotic arms to display anthropomorphic behaviour is further explored in the interactive installation “Mimic”, where visitors are allowed to communicate with a robotic arm through gestures (Watson, Gobeille and Hardeman, 2017). While Hinwood et al. used the WOZ method to control robotic interaction, this installation tracks the movement of people in the space with a Kinect Camera and translate these data into robotic reactions, seeking to display feelings such as trust, interest and curiosity. The “Mimic” project thereby showcases the potentials of providing a robotic arm with the ability to “see” people within close proximity and to engage in a dialogue based solely on body language. By constructing a similar robotic installation, although with a larger robotic arm and utilising several cameras/sensors, artist and robotics researcher Madeline Gannon tried to evoke a sense of robotic personality and aimed for people to contemplate their co-existence with intelligent machines (Gannon, 2018). With a system for people tracking and people ranking, the robot could locate people’s faces and “look” at the visitors face-to-face. In reflecting upon the advantages of robotic body language, Gannon argues that the display of intentions and imitation of emotions can:

> *"… serve a tactical purpose. For example, the ability to externally broadcast the internal state of mind of an autonomous robot could be very useful when it is about to something dangerous. This legibility would let the robot produces an affect to instinctually prompt people to step back away from danger."* (Gannon, 2018)

Building upon such insight, implementing robotic body language and gestures within design methods for human-robot co-creation might allow designers to engage in non-verbal communication, understand shared design intentions, work more proficient in tasks requiring turn-taking within shared workspaces, and explore design solutions that accommodate shared goals.

3.3.7 Summary

The intention of the sub-chapter on Creative Robotic Processes was to elaborate on current implementations of robotic arms in architectural research and identify existing design methods that supports creative human-robot design exploration.

By accounting for the robotic classifications and definitions suggested by Robin R. Murphy (Murphy, 2019), the relevance of the joint cognitive systems was discussed and the prospect of co-exploring a material system with a sensing and reacting robot, was proposed to be in line with the architectural vision and research objectives of the thesis. Later elaborations on the implementation of sensory devices and with it the extended acting capabilities of the robot, encouraged further exploration of novel processes for creative design explorations in which both human and robot holds the capacity to sense and interact. In realising the creative potential for new design methods that enable human-robot co-creation, a deeper appreciation of the great technical and methodological challenges related to such advancements was found to be essential. With the aim of the thesis being to investigate the creative impact of implementing such co-creative human-robot design methods, it was concluded that new research inquiries should be based on the exploration of simple robot-as-tool design methods. The purpose of such research investigations being to construct a platform of situated knowledge on which to base further research inquiries.

A survey of existing research within architectural robotics lead to the identification of five distinct approaches for the implementation of robots within design processes. By examining the information- and design workflow related to each unique design approach, an elaboration on their specific constraints and opportunities was offered. A comparison of the creative potentials related to each of the robot-based workflows supports the view that creativity, or at least the support thereof, is present within all the exemplified workflows. In addition, and essential for further investigations on methods for creative human-robot design exploration, it can be argued that the exact placement, duration and influence of the creative process is highly dependent on the established workflows and their implementation of feedback systems. In this respect, the workflow associated with human-robot co-creation was identified as having the highest potential for supporting the development of creative human-robot design processes.

Finally, a short review on existing research related to creativity and the use of robotic arms from within the field of HRI revealed relevant questions towards the role of shared intentions and placement of control. Through an examination of artistic work exploring collaborative human-robot drawing tasks, the potential in establishing anthropomorphic relationship between humans and robotic arms was identified. Further supported by the work of Madeline Gannon it was argued that the robotic display of anthropomorphic behavior, or robotic body language, could serve as a method for "*externally broadcasting the internal state of mind of an autonomous robot"* (Gannon, 2018). The implementation of such robotic gestures might allow for improved collaboration in future design methods for human-robot co-creation.

References

Aejmelaeus-Lindström, P. *et al.* (2016) "Jammed architectural structures: towards large-scale reversible construction," *Granular Matter*, 18(2), p. 28. doi: 10.1007/s10035-016-0628-y.

AIArtists.org (2021) *Sougwen Chung*. Available at: https://aiartists.org/sougwen-chung.

Aish, R. and Hanna, S. (2017) "Comparative evaluation of parametric design systems for teaching design computation," *Design Studies*, 52, pp. 144–172. doi: 10.1016/j.destud.2017.05.002.

Alvarez, M. E. *et al.* (2019) "Tailored Structures, Robotic Sewing of Wooden Shells," in Willmann, J. et al. (eds) *Robotic Fabrication in Architecture, Art and Design 2018*. Cham: Springer International Publishing, pp. 405–420. doi: 10.1007/978-3-319-92294-2_31.

Baartman, L. K. J. and de Bruijn, E. (2011) "Integrating knowledge, skills and attitudes: Conceptualising learning processes towards vocational competence," *Educational Research Review*, 6(2), pp. 125–134. doi: 10.1016/j.edurev.2011.03.001.

Bernal, M., Haymaker, J. R. and Eastman, C. (2015) "On the role of computational support for designers in action," *Design Studies*, 41, pp. 163–182. doi: 10.1016/j.destud.2015.08.001.

Boden, M. A. (2004) *The Creative Mind: Myths and Mechanisms*. 2nd editio. London: Routledge.

Braumann, J. and Brell-cokcan, S. (2015) "Adaptive Robot Control - New Parametric Workflows Directly from Design to KUKA Robots," in Martens, B. et al. (eds) *Proceedings of the 33rd eCAADe Conference*. Vienna University of Technology, Vienna, Austria, pp. 243–250. Available at: http://papers.cumincad.org/cgi-bin/works/Show?_id=ecaade2015_100&sort=DEFAULT&search=robot&hits=109.

Braumann, J., Stumm, S. and Brell-Çokcan, S. (2018) "Accessible Robotics," in Dass, M. and Wit, A. J. (eds) *Towards a Robotic Architecture2*. Applied Research and Design Publishing, pp. 154–165.

Brell-Çokcan, S. and Braumann, J. (2011) "Parametric Robot Control," *Proceedings of the 31st Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA)*, pp. 242–251.

Brell-Çokcan, S. and Braumann, J. (eds) (2013) *Rob | Arch 2012*. Vienna: Springer Vienna. doi: 10.1007/978-3-7091-1465-0.

Briggs, R. O. and Reinig, B. A. (2010) "Bounded ideation theory," *Journal of Management Information Systems*, 27(1), pp. 123–144. doi: 10.2753/MIS0742-1222270106.

Brugnaro, G. *et al.* (2016) "Robotic Softness: An Adaptive Robotic Fabrication Process for Woven Structures," in *ACADIA 2016: POSTHUMAN FRONTIERS: Data, Designers, and Cognitive Machines*.

Brugnaro, G. and Hanna, S. (2019) "Adaptive Robotic Carving," in *Robotic Fabrication in Architecture, Art and Design 2018*. Cham: Springer International Publishing, pp. 336–348. doi: 10.1007/978-3-319-92294-2_26.

Brugnaro, G., Vasey, L. and Menges, A. (2008) "An Adaptive Robotic Fabrication Process for Woven Structures," in *ACADIA // 2016 Posthuman Frontiers: Data, Designers, and Cognitive Machines*, pp. 154–163. Available at: http://papers.cumincad.org/data/works/att/acadia16_154.pdf.

Chung, S. (2019) *Why I draw with robots (TEDtalk)*. Available at: https://www.youtube.com/watch?v=q-GXV4Fd1oA.

Clifford, B. *et al.* (2014) "Variable Carving Volume Casting - A Method for Mass-Customized Mold Making," in Mcgee, W. and de Leon, M. P. (eds) *Robotic Fabrication in Architecture, Art and Design 2014*. Springer, pp. 3–15. doi: 10.1007/978-3-319-26378-6.

Csikszentmihalyi, M. (2014a) "Creativity and Genius: A Systems Perspective," in *The Systems Model of Creativity*. Dordrecht: Springer Netherlands, pp. 99–125. doi: 10.1007/978-94-017-9085-7_8.

Csikszentmihalyi, M. (2014b) "Society, Culture, and Person: A Systems View of Creativity," in *The Systems Model of Creativity*. Dordrecht: Springer Netherlands, pp. 47–61. doi: 10.1007/978-94-017-9085-7_4.

Csikszentmihalyi, M. (2014c) *The Systems Model of Creativity*. Dordrecht: Springer Netherlands. doi: 10.1007/978-94-017-9085-7.

Csikszentmihalyi, M. and Nakamura, J. (2006) "Creativity Through the Life Span from an Evolutionary Systems Perspective," in Hoare, C. (ed.) *Handbook of Adult Development and Learning*. New York: Oxford University Press, pp. 243–254. doi: http://www.oup.com.

Csikszentmihalyi, M. and Wolfe, R. (2014) “New Conceptions and Research Approaches to Creativity: Implications of a Systems Perspective for Creativity in Education,” in *The Systems Model of Creativity*. Dordrecht: Springer Netherlands, pp. 161–184. doi: http://link.springer.com/10.1007/978-94-017-9085-7_10.

Darke, J. (1979) “The primary generator and the design process,” *Design Studies*, 1(1), pp. 36–44. doi: 10.1016/0142-694X(79)90027-9.

Davis, D., Burry, J. and Burry, M. (2011) “The flexiblity of logic programming,” in Herr, C. M. et al. (eds) *Circuit Bending, Breaking and Mending: Proceedings of the 16th International Conference on Computer-Aided Architectural Design Research in Asia*. Hong Kong: Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), pp. 29–38.

Dijksterhuis, A. and Meurs, T. (2006) “Where creativity resides: The generative power of unconscious thought,” *Consciousness and Cognition*, 15(1), pp. 135–146. doi: 10.1016/j.concog.2005.04.007.

Doerstelmann, M., Knippers, J., Menges, A., *et al.* (2015) “ICD/ITKE Research Pavilion 2013-14: Modular Coreless Filament Winding Based on Beetle Elytra,” *Architectural Design*, 85(5), pp. 54–59. doi: 10.1002/ad.1954.

Doerstelmann, M., Knippers, J., Koslowski, V., *et al.* (2015a) “ICD/ITKE Research Pavilion 2014-15: Fibre Placement on a Pneumatic Body Based on a Water Spider Web,” *Architectural Design*, 85(5), pp. 60–65. doi: 10.1002/ad.1955.

Doerstelmann, M., Knippers, J., Koslowski, V., *et al.* (2015b) “ICD/ITKE Research Pavilion 2014-15: Fibre Placement on a Pneumatic Body Based on a Water Spider Web,” *Architectural Design*, 85(5), pp. 60–65. doi: 10.1002/ad.1955.

Dörfler, K., Rist, F. and Rust, R. (2013) “Interlacing,” in *Rob | Arch 2012*. Vienna: Springer Vienna, pp. 82–91. doi: 10.1007/978-3-7091-1465-0_7.

Dorst, K. and Cross, N. (2001) “Creativity in the design process: Co-evolution of problem-solution,” *Design Studies*, 22(5), pp. 425–437. doi: 10.1016/S0142-694X(01)00009-6.

Dubor, A. *et al.* (2016) “Sensors and Workflow Evolutions: Developing a Framework for Instant Robotic Toolpath Revision,” in Reinhardt, D., Saunders, R., and Burry, J. (eds) *Robotic Fabrication in Architecture, Art and Design 2016*. Cham: Springer International Publishing, pp. 410–425. doi: 10.1007/978-3-319-26378-6_33.

Dunn, N. (2012) *Digital Fabrication in Architecture*, *Computer*. doi: 10.1007/s00004-012-0130-8.

Elashry, K. and Glynn, R. (2014) “An Approach to Automated Construction Using Adaptive Programing,” in McGee, W. and de Leon, M. P. (eds) *Robotic Fabrication in Architecture, Art and Design 2014*. Cham: Springer International Publishing, pp. 51–66. doi: 10.1007/978-3-319-04663-1_4.

Frank, F., Wang, S.-Y. and Sheng, Y.-T. (2015) *Taco ABB*. Available at: http://blickfeld7.com/architecture/rhino/grasshopper/Taco/ (Accessed: June 3, 2020).

Frith, C. (2007) *Making Up the Mind - How the Brain Creates Our Mental World*. Oxford: Blackwell Publishing.

Gannon, M. (2018) *Human-Centered Interfaces for Autonomous Fabrication Machines*. Available at: https://static1.squarespace.com/static/5758289d27d4bdf581e1c031/t/5b79b0bd88251b5c02217e90/1534701771028/2018-Gannon-Dissertation_Human-Centered_Interfaces_Autonomous_Fab.pdf.

García del Castillo Y López, J. L. (2019) *Enactive Robotics: An Action-State Model for Concurrent Machine Control*. Available at: http://nrs.harvard.edu/urn-3:HUL.InstRepos:41021631.

García del Castillo y López, L. J. (2019) “Robot Ex Machina,” in *ACADIA // 2019 Ubiquity and Autonomy. Paper Proceedings of the 39th Annual Conference of the Association for Computer Aided Design in Architecture*, pp. 40–49.

Getzels, J. W. and Csikszentmihalyi, M. (1976) *The Creative Vision: a longitudinal study of problem finding in art*. New York: Wiley.

Gramazio, F., Kohler, M. and Willmann, J. (2014) *The Robotic Touch - How Robots Change Architecture*. 1st edn. Zurich: Park Books.

Guilford, J. P. (1967) *The Nature of Human Intelligence*. New York: McGraw-Hill.

Hakak, A. M., Biloria, N. and Venhari, A. A. (2014) “Creativity in Architecture—A Review on Effective Parameters Correlated with Creativity in Architectural Design,” *Journal of Civil Engineering and Architecture*, 8(11), pp. 1371–1379. doi: 10.17265/1934-7359/2014.11.003.

Hektner, J. and Asakawa, K. (2000) “Learning to like challenges,” in Csikszentmihalyi, M. and Schneider, B. (eds) *Becoming adult*. New York: Basic Books, pp. 95–112.

Hillier, B., Musgrove, J. and O’Sullivan, P. (1972) “Knowledge and Design,” *Environmental Design: Research and Practice*, pp. 245–264.

Hinwood, D. *et al.* (2018) “A Proposed Wizard of OZ Architecture for a Human-Robot Collaborative Drawing Task,” in Ge, S. S. et al. (eds) *International Conference on Social Robotics (ICSR 2018)*. Cham: Springer International Publishing (Lecture Notes in Computer Science), pp. 35–44. doi: 10.1007/978-3-030-05204-1_4.

Jeffers, M. (2016) “Autonomous Robotic Assembly with Variable Material Properties,” in Reinhardt, D., Saunders, R., and Burry, J. (eds) *Robotic Fabrication in Architecture, Art and Design 2016*. Cham: Springer International Publishing, pp. 48–61. doi: 10.1007/978-3-319-26378-6_4.

Johns, R. L. (2014) “Augmented Materiality: Modelling with Material Indeterminacy,” in *Fabricate 2014*. gta Verlag, Zurich, pp. 216–223. doi: 10.2307/j.ctt1tp3c5w.30.

Johns, R. L., Kilian, A. and Foley, N. (2014) “Design Approaches Through Augmented Materiality and Embodied Computation,” in *Robotic Fabrication in Architecture, Art and Design 2014*. Cham: Springer International Publishing, pp. 319–332. doi: 10.1007/978-3-319-04663-1_22.

Jones, D. (2012) *The Aha! Moment: A Scientist’s Take on Creativity*. Johns Hopkins University Press.

Kandel, E. R. (2012) *The age of insight: the quest to understand the unconscious in art, mind, and brain, from Vienna 1900 to the present*. New York: Random House.

Kandel, E. R. (2016) *Reductionism in art and brain science: bridging the two cultures*. New York: Columbia University Press.

Keating, S. *et al.* (2014) “A Compound Arm Approach to Digital Construction,” in *Robotic Fabrication in Architecture, Art and Design 2014*. Cham: Springer International Publishing, pp. 99–110. doi: 10.1007/978-3-319-04663-1_7.

Kilian, A. (2006) *Design Explorations through Bidirectional Modeling of Constraints*. Available at: http://www.designexplorer.net/download/Kilian-phd-arch-2006.pdf.

King, N. and Grinham, J. (2013) “Automating Eclipsis,” in *Rob | Arch 2012*. Vienna: Springer Vienna, pp. 214–221. doi: 10.1007/978-3-7091-1465-0_25.

Knippers, J. *et al.* (2015) “ICD/ITKE Research Pavilion 2012: Coreless Filament Winding Based on the Morphological Principles of an Arthropod Exoskeleton,” *Architectural Design*, 85(5), pp. 48–53. doi: 10.1002/ad.1953.

Lawson, B. (2005) *How Designers Think - The Design Process Demystified*. 4th editio. Taylor & Francis.

Maher, M. lou (1994) “Creative design using a genetic algorithm,” in Khozeimeh, K. (ed.) *Computing in Civil Engineering*. Nwe York: American Society of Civil Engineers, pp. 2014–2021.

Maher, M. and Tang, H.-H. (2003) “Co-evolution as a computational and cognitive model of design,” *Research in Engineering Design*, 14(1), pp. 47–64. doi: 10.1007/s00163-002-0016-y.

Marzke, M. W. (1997) “Precision grips, hand morphology, and tools,” *American Journal of Physical Anthropology*, 102(1), pp. 91–110. doi: 10.1002/(SICI)1096-8644(199701)102:1<91::AID-AJPA8>3.0.CO;2-G.

McGee, W. *et al.* (2017) “Infundibuliforms: Kinetic systems, Additive Manufacturing for Cable Nets and Tensile Surface Control,” in *Fabricate 2017*. UCL Press, pp. 84–91. doi: 10.2307/j.ctt1n7qkg7.15.

McGee, W., Ng, T. Y. and Peller, A. (2019) “Hard + Soft: Robotic Needle Felting for Nonwoven Textiles,” in *Robotic Fabrication in Architecture, Art and Design 2018*. Cham: Springer International Publishing, pp. 192–204. doi: 10.1007/978-3-319-92294-2_15.

Merleau-Ponty, M. (2013) *Phenomenology of Perception*. London: Routledge. doi: 10.4324/9780203720714.

Murphy, R. R. (2019) *Introduction to AI Robotics*. 2nd edn. Cambridge, MA: MIT Press.

Nakamura, J. and Csikszentmihalyi, M. (2005) "The Concept of Flow," in Snyder, C. R. and Lopez, S. J. (eds) *Handbook of Positive Psychology*. 2nd edn. New York: Oxford University Press, pp. 89–105.

Nicholas, P. *et al.* (2015) "A Multiscale Adaptive Mesh Refinement Approach to Architectured Steel Specification in the Design of a Frameless Stressed Skin Structure," in *Modelling Behaviour*. Cham: Springer International Publishing, pp. 17–34. doi: 10.1007/978-3-319-24208-8_2.

Oxman, R. (2006) "Theory and design in the first digital age," *Design Studies*, 27(3), pp. 229–265. doi: 10.1016/j.destud.2005.11.002.

Pazik, K. (2019) "Mockup Method: Heuristic Architectural Fragments as Central Models in Architectural Design," in Willmann, J. et al. (eds) *Robotic Fabrication in Architecture, Art and Design 2018*. Springer, pp. 31–43. doi: 10.1007/978-3-319-92294-2_3.

Peng, H. *et al.* (2018) "Roma: Interactive fabrication with augmented reality and a Robotic 3D printer," *Conference on Human Factors in Computing Systems - Proceedings*, 2018-April. doi: 10.1145/3173574.3174153.

Reinhardt, D. (2019) "Design Robotics - Towards human-robot timber module assembly," in *Architecture in the Age of the 4th Industrial Revolution - Proceedings of the 37th eCAADe and 23rd SIGraDi Conference*. São Paulo: Editora Blucher, pp. 211–216.

Robertson, B. F. and Radcliffe, D. F. (2009) "Impact of CAD tools on creative problem solving in engineering design," *CAD Computer Aided Design*, 41(3), pp. 136–146. doi: 10.1016/j.cad.2008.06.007.

Rowe, P. G. (1986) *Design Thinking*. Cambridge, MA: MIT Press. Available at: https://mitpress.mit.edu/books/design-thinking.

Rowe, P. G. (2017) *Design Thinking in the Digital Age*. Cambridge, MA: Harvard University Graduate School of Design and Sternberg Press.

Rutten, D. (2013) "Galapagos: On the logic and limitations of generic solvers," *Architectural Design*, 83(2), pp. 132–135. doi: 10.1002/ad.1568.

Sanders, E. B.-N. and Stappers, P. J. (2008) "Co-creation and the new landscapes of design," *CoDesign*, 4(1), pp. 5–18. doi: 10.1080/15710880701875068.

Saunders, A. and Epps, G. (2016) "Robotic Lattice Smock," in Reinhardt, D., Saunders, R., and Burry, J. (eds) *Robotic Fabrication in Architecture, Art and Design 2016*. Cham: Springer International Publishing, pp. 78–91. doi: 10.1007/978-3-319-26378-6_6.

Schön, D. A. (1983) *The Reflective Practitioner - How Professionals Think in Action*. 1. edition. Basic Books.

Schumann, K. and Johns, R. L. (2019) "Airforming - Adaptive Robotic Molding of Freeform Surfaces through Incremental Heat and Variable Pressure," in Haeusler, M., Schnabel, M. A., and Fukuda, T. (eds) *Intelligent & Informed - Proceedings of the 24th CAADRIA Conference - Volume 1*. Wellington, New Zealand, pp. 33–42. Available at: http://papers.cumincad.org/cgi-bin/works/paper/caadria2019_648.

Schwartz, T. (2013) "HAL: Extension of a visual programming language to support teaching and research on robotics applied to construction," in *Rob | Arch 2012*. Vienna: Springer Vienna, pp. 92–101. doi: 10.1007/978-3-7091-1465-0_8.

Sennett, R. (2008) *The Craftsman*. London: Penguin Books.

Søndergaard, A. *et al.* (2016) "Robotic Hot-Blade Cutting," in Reinhardt, D., Saunders, R., and Burry, J. (eds) *Robotic Fabrication in Architecture, Art and Design 2016*. Cham: Springer International Publishing, pp. 150–164. doi: 10.1007/978-3-319-26378-6_11.

Stumm, S., Devadass, P. and Brell-Cokcan, S. (2018) "Haptic programming in construction," *Construction Robotics*, 2(1–4), pp. 3–13. doi: 10.1007/s41693-018-0015-9.

Sutherland, I. E. (1963) *Sketchpad, a Man-machine Graphical Communication System*. Available at: https://dspace.mit.edu/handle/1721.1/14979.

Terzidis, K. (2006) *Algorithmic Architecture*. Architectural Press, Elsevier. Available at: https://www.academia.edu/5003686/_009801309_architecture_ebook_algorithmic_architecture.

UR (2020) *Universal Robots' Homepage*. Available at: https://www.universal-robots.com (Accessed: December 28, 2020).

Vasey, L. *et al.* (2016) "Collaborative Construction: Human and Robotic Collaboration Enabling the Fabrication and Assembly of a Filament-Wound Structure," in *ACADIA 2016: Posthuman Frontiers: Data, Designers, and Cognitive Machines - Proceedings of the 36th Annual Conference of the Association for Computer Aided Design in Architecture*. Ann Arbor, pp. 184–195. Available at: http://papers.cumincad.org/cgi-bin/works/paper/acadia16_184.

Vasey, L., Maxwell, I. and Pigram, D. (2014) "Adaptive Part Variation," in *Robotic Fabrication in Architecture, Art and Design 2014*. Cham: Springer International Publishing, pp. 291–304. doi: 10.1007/978-3-319-04663-1_20.

Visose (2016) *Robots - Grasshopper plugin for programming robots*. Available at: https://github.com/visose/Robots/ (Accessed: June 1, 2019).

Watson, T., Gobeille, E. and Hardeman, N. (2017) *Mimic*, *Design I/O*. Available at: https://www.design-io.com/projects/mimic (Accessed: December 7, 2020).

Woodbury, R. (2010) *Elements of Parametric Design*. 1st edn. Oxford: Routledge.

Wujec, T. (2017) *The Future of Making*. Melcher Media.

van Zak, J. *et al.* (2018) "Parametric Chemistry: Reverse-engineering Biomaterial Composite Structures for Robotic Manufacturing of Bio-Cement Structures across Scales," in Daas, M. and Wit, A. J. (eds) *Towards a Robotic Architecture*. Applied Research and Design Publishing, pp. 216–229.

4.

Informed Robotic Design Exploration

4.1 Introduction

Based on the arguments framed in the Methodology chapter, the thesis employs an explorative 'research through design' strategy to investigate the potential role and impact of integrating co-creative robots in the architectural design process. Following this experiment-driven research strategy, the knowledge created in this thesis is based on the implementation of consecutive design experiments - each uncovering essential findings that guide the research trajectory for the following experiment.

The following three sections describe the nature and scope of each design experiment and present the results, insights, and knowledge gained. Based on the scope of the research experiments, and for communicative purposes, they are grouped in three categories of 'robotic design exploration': 'Informed', 'Interactive', and 'Collaborative' and presented in chapter 4, 5, and 6, respectively. Although grouped in the three categories, the research experiments are still arranged and presented in their chronological order, offering an insight into the progression of the explorative research journey.

Following the dissemination strategy described in section 2.3. each design experiment has been disseminated through peer-reviewed publications. Due to the scope and theme of the selected publication channels, some aspects of the acquired knowledge has out of necessity been reduced, or in some cases omitted, from the published articles. Therefore, to allow for proper depth and coherence in the dissemination of the research studies, the description of each design study is initiated with reference to the associated research paper (presented in the appendix) followed by an extended and thorough elaboration of previously omitted content as well as relevant insights gained in subsequent studies.

To ease communication, the presentation of each study adheres to the same structural build-up, starting with an 'introduction' to the aim of the research experiment followed by the extended elaboration on the study. For each study the extended writings follow the same structure; starting with the 'methods', then the 'explorations' and their associated design outcomes, followed by the 'results' of the design experiments, ending with the 'conclusion' and 'discussion' to sum up the acquired knowledge and establish the trajectory and adjusted focus for future studies.

Figure 4.1.
The full scale concrete demonstrator assembled in the court yard of the Utzon Center, Aalborg, Denmark. Photo by Mads Brath Jensen.

4.2 Design Study 1: Robotic Concrete Printing

4.2.1 Introduction

In the light of the objective of this thesis, to formulate and establish a framework for robotic-driven design exploration, it is relevant to study the implications of applying robotic fabrication to a creative design process and investigate how modes of robotic simulation and -fabrication can influence and merge with established modes of computational-driven design. By establishing such an explorative design framework investigations of both physical- and computational-driven design problems can be bridged, enabling the architect to engage in an integrated human-robot-material design process.

The background on previous solutions is based on recent work in the field of robotic architecture and parametric design, where the development of methods and digital tools for simulating and controlling industrial robotic arms, has narrowed the gap between virtual and physical design spaces, as described in chapter 1 and 3. The technological and methodological development associated with robotic architecture supports a material-informed and fabrication-driven design process, also described in chapter 1 and 3, and allows an engagement in material processes that features high geometric complexity and multi-performance design criteria. The power, flexibility and precise movements of robotic arms combined with the visual-based parametric control and simulation tools, as with the robot control tool KUKAprc developed by the Association of Robots in Architecture (Brell-Çokcan and Braumann, 2010), enables architects to explore processes of material making and its potential impact on architectural conditions - the robotic arm thereby becomes the mediator between computational design and material making.

A parametric design model that integrates geometric exploration, simulation of contextual conditions, and simulation of robotic fabrication serve as the background for potential solutions. Combined with a physical setup, consisting of an industrial robotic arm and a custom made end effector for material extrusion, a design framework can be established and serve as a method for exploring a material system and its inherent performative aspects. Due to its capacity for thermal accumulation of solar radiation, concrete is used as the material component during the study and spatial distribution of concrete through robotic-controlled extrusion serves as the fabrication method.

Through the development of a design framework that enables and facilitates robot-driven design exploration, this study attempts to elicit the potential challenges and benefits associated with the integration of robotic fabrication in the early phases of design exploration.

The study presents a parametric design model, a robotic simulation model, a thermal simulation model, an evolutionary search model, and a robotic fabrication setup. The explorative design process, facilitated by combining these models into an integrated design framework, resulted in a 1:1 physical demonstrator, showcasing the potentials and challenges of utilising the robotic-driven design framework.

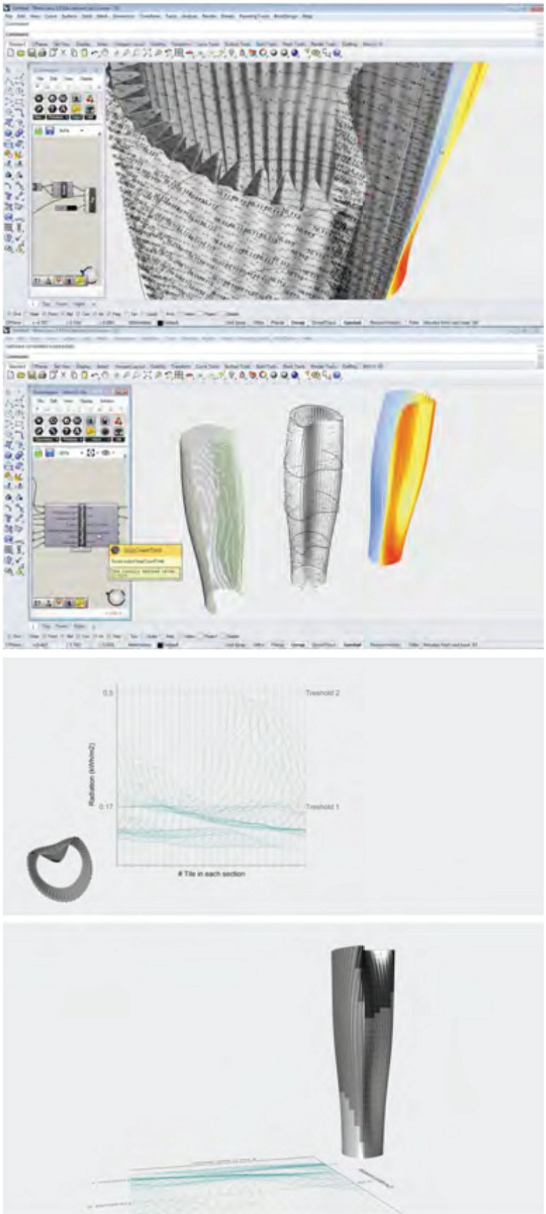


Figure 4.2.
Visual feedback from the computational design framework. From the top: (1) close-up of the visual design model. (2) fabricational model (left), design model (centre), thermal simulation model (right). (3+4) Interface of the dynamic material distribution model. Each curve represent a horisontal section through the global form, and the solar energy for a specific periodfalling on this part of the form. The treshold lines, which are open to input from the designer, then determines at what energy level what colour/material should be placed where. Screenshots by Mads Brath Jensen

The study has been disseminated through the conference paper "Thermal Compositions Through Robot Based Thermal Mass Distribution" (Appendix A), referred to as 'Paper 1'. As this paper presented parts of the methods, results and discussion associated with this study, several of the following paragraphs features rephrased fragments and references to this publication.

4.2.2 Methods

As presented in 'Paper 1', the study applies a series of methods to inform and facilitate a robotic-based design process that allows for a parallel investigation of parametric design options, thermal performance, material properties and robotic fabrication. The combination of these methods makes up a design framework used as a driver for examining the potential role of robotic fabrication in design exploration. 'Paper 1' focused on the methods for thermal simulation and only briefly touched upon the configuration of the collected design framework, as outlined in the diagram in 1.4. As the objective of this PhD thesis is to investigate how robotic fabrication can contribute to a creative design process, it is essential to establish and advance the design framework. Therefore the following section elaborates on two critical aspects of the proposed design framework: the computational design framework and the robotic fabrication setup.

The Computational Design Framework

As described in 'Paper 1', the computational framework is developed in the parametric CAD environment Rhinoceros/Grasshopper by McNeel Inc. as this environment affords the use of both existing simulation tools and customised tools for extending the capabilities of the default version. The computational model is structured into four main models: a parametric design model, a thermal simulation model, a robotic simulation model, and a model featuring an evolutionary search algorithm.

The thermal simulation model and its ability to compute received solar energy on the global form is thoroughly described in the method section of 'Paper 1' and for this study does not need further elaboration.

The parametric design model contains the parametric definition that geometrically defines the global form of the design solution. The development of the global form is based on previous studies on thermally optimised forms conducted by Isak W. Foged (Foged, 2013) and is generated from five vertically-distributed plan sections, as visualised in figure 4.2. The inner and outer curve in each section can be reconfigured on a macro level through a series of curve control points and on a micro level through locally increasing/decreasing the amplitude of the curve waves, thereby changing the length and orientation of the curves/surface allowing the global form to respond to local solar gain on the surfaces, as described in 'Paper 1'. Throughout the explorative design process, the design model was used a tool for storing new knowledge and iteratively introducing new design variables or updating the value or numeric domain of existing variables - gradually shaping the design model and the problem-space it defines.

Figure 4.3.
Development of prototypes for the concrete extrusion system.
Version 1: Linear actuator ram originally designed for clay extrusion, by www.3dpotter.com
Version 2: Peristaltic pump from Köster connected to a custom nozzle with a single hose.
Version 3: A concrete pump from MAI with a custom nozzle for direct extrusion without hose.
Final version: Setup with two concrete pumps from MAI. A 'feed pump' at the floor connected with hoses to an 'extrusion pump' mounted on the robot arm.
Photos by Mads Brath Jensen

The model for robotic simulation and control contains a procedure for slicing the individual bricks into layers and subsequently distributing target planes for robotic simulation along these layer curves, an established method used in most 3D printing applications. Variables such as layer height, density/resolution of target planes, printing speed, and maximum printing dimensions, were all parametrically interrelated and final values determined based on the continuous experimentation and prototyping, where brick size and weight was restricted to permit manual placement by a mason, and ensure that the bricks maintain their shape during fabrication. The model for robotic simulation and control uses the Grasshopper add-on KUKAprc (Brell-Çokcan and Braumann, 2010). This add-on features parametric robot control and allows for visual simulation of robot positions and generation of a robot program that can be fed directly to any KUKA robot. To ensure a reliable comparison between the computational simulation of the robot and the real-world robotic fabrication process, a 3D model of the physical robotic setup was established, including the fabrication table and the concrete extrusion setup. With the global form consisting of more than 300 individual bricks and three colours of concrete material, the robotic simulation features a system for management and planning of the fabrication process. This system handles the distribution and orientation of bricks on a production table and inspects for possible collisions during fabrication.

Robotic Fabrication Setup

The physical robotic setup consists of a KUKA KR300 R2500 robotic arm and a fabrication table with a surface area of 1300x1300 mm. To facilitate the printing of individual concrete bricks, nine plates of 400x400 mm phenolic film faced plywood was arranged on the fabrication table in a 3x3 matrix. The film-coated fabrication plates allow for fast replacement during fabrication as each plate can be replaced by a new empty plate and fabrication can resume while the printed concrete element is set in a storage area and ensured an optimal curing process protected against loss of moisture with plastic sheets.

The custom-built concrete extrusion setup is constructed to ensure a controlled and consistent flow of concrete. The process of developing a custom extrusion setup involved construction and testing of several different systems (see figure 4.3), with the final setup consisting of two industrial mortar-pumps (MAI®2PUMP-PICTOR), an 'extrusion pump' mounted on the robotic arm in a custom fixture and a 'feed pump' placed on the floor next to the fabrication table. The two mortar pumps are connected through a high-pressure hose, the 'feed pump' is connected using a standard GEKA coupler and the 'extrusion pump' by a custom 3D printed plastic adapter. To avoid pressure build-up inside the extrusion system, it features an overflow hose which returns excess concrete to the feed pump - an overflow system that allows for continuous material flow through the two hoses, helping to overcome issues with clogging due to setting of the concrete. During fabrication, the 'feed pump' is always turned on, for the reason just described, while the 'extrusion pump' is wired to an output signal on the robotic system allowing the extrusion to be controlled by the code in the robot program. This allows for precise start/stop of the extrusion process similar to that of standard extrusion-based 3D printers.

Figure 4.4.
Experiments with the concrete material system. Several extruded prototypes were fabricated to investigate the connection between nozzle size, extrusion flowrate and material mixing ratios.
Photos by Mads Brath Jensen

4.2.3 Results

The results described in 'Paper 1' featured two very concise statements: "*the results of the study are the method and model of addressing and designing with robot based extrusion constructions related to questions of thermal performance.*" and that "*the computational model/method developed furthermore allowed for a variety of design inputs with each their parameter set, from colouration, material density, spatial composition of extruded layers, PCM mixture and element assembly organisation.*" (Appendix A)

As this study seeks to understand the requirements for, and potentials in, establishing a design framework that implements robotic fabrication and allows for a parallel exploration of both form, material, performance, and fabrication, additional results are essential to point out.

The study finds that exploring design options with the computational design system and designing the computational design system itself is an important aspect and that introducing robotic fabrication into this process leads to an extension of this task, also involving the design of the physical fabrication system. The results of the study thereby suggest that to fully exploit a robotic-based design framework and explore all the mentioned design modes, the designer needs an extended skill-set.

Choice of material system and fabrication technology is found to have a significant impact on the framing/scope and manoeuvrability of robotic-based design exploration. For this specific study, the process of developing the bespoke concrete extrusion system demanded both knowledge and skills within the material field of rheology of concrete and the mechanical engineering of pressurised pumping and extrusion systems.

The study also finds that although a gradually re-defined problem-solution space confines the computational-based design framework, it continues to support a creative, explorative and non-deterministic design process. However, this is not the case for the robotic-based fabrication process, where the very deterministic nature of robot programming and file-to-factory workflow, leaves no room for human interaction or unexpected creative input.

4.2.4 Conclusion

Based on the result of the study it can be concluded that integration of robotic fabrication has a significant impact on how a computational-driven design process unfolds and that it forces the design exploration towards a rational, material-based, and realistic design response. The proposed computational framework shows that integration of a design model, a thermal simulation model, a robotic simulation model, and a genetic search algorithm, allows for exploration of a combined problem-solution space, which can be continuously informed and adapted to the result of successive physical investigations.

The computational model allows for a parametrisation of a wide range of design

Figure 4.5.
The full-scale concrete demonstrator during assembly. Vertical steel rods anchored in the concrete base are added to the construction to ensure structural integrity.
Photo by Mads Brath Jensen.

input, from controlling the global form, to partition into individual elements, variations in material density, assignment of material colour, specification of extrusion layer height, and adjustment of simulated robot speed. This parametrisation of the computational design model allows for exploration of various design options within the solution space, but also the exploration of the restrictions and limitations within the problem space. Pursuing the design exploration through a parallel investigation of both the computational model, the physical robot-based fabrication setup and the material behaviour allows for a continuous and iterative re-structuring and re-designing of the parametric relationships to capture and reinforce desirable features and behaviours.

The applicability of the custom-build robotic-driven extrusion system is validated through the development of the 1:1 scale demonstrator comprising fabrication of more than 300 bricks (see figure 4.1). Control of the extrusion pump takes place through the robot control code, which is automatically generated within the computational design model. As restrictions for the extrusion system is implemented within the parameter space of the computational design model, it is ensured that all design variations are producible. Design and fabrication of the extrusion system is, however, a challenging task, mostly because the mixed concrete changes consistency during the fabrication session and that irregular effects, caused either during mixing of the concrete or by the friction between the concrete and the inner surfaces of the feeding/pump system, can result in unstable and structurally deficient outcomes.

The investigated design framework implements robotic fabrication as both a design parameter during the process of early design exploration and as a means for physical design making. In contrast, the final assembly phase is performed manually through a standard human-based brick stacking procedure. As the global form of the demonstrator contains a continuous double-curved surface build with rounded concrete bricks placed in an irregular pattern, the visual tracing of lines and edge-to-edge brick connections is problematic. The lack of methods for performing control measurements during the stacking procedure resulted in escalating inaccuracies for each consecutive layer, especially prominent in the concave region where the tracing of the ingoing curvature was illegible.

4.2.5 Discussion

A robotic-based design framework

The design framework established in this study has shown to support and inform an explorative design process where robotic-based extrusion of concrete material is informed by thermal simulation thereby providing "*new design strategies for aesthetic oriented environmental passive architectures.*"(Foged and Jensen, 2018) . As can be seen in the schematic overview in figure 4.7, the robotic-based design framework, encompassing both the robotic fabrication setup, the material system, and the computational design framework, allowed for a seamless iterative exploration of geometric variations and their corresponding environmental performance and constructability. By implementing methods and techniques for extrusion-based

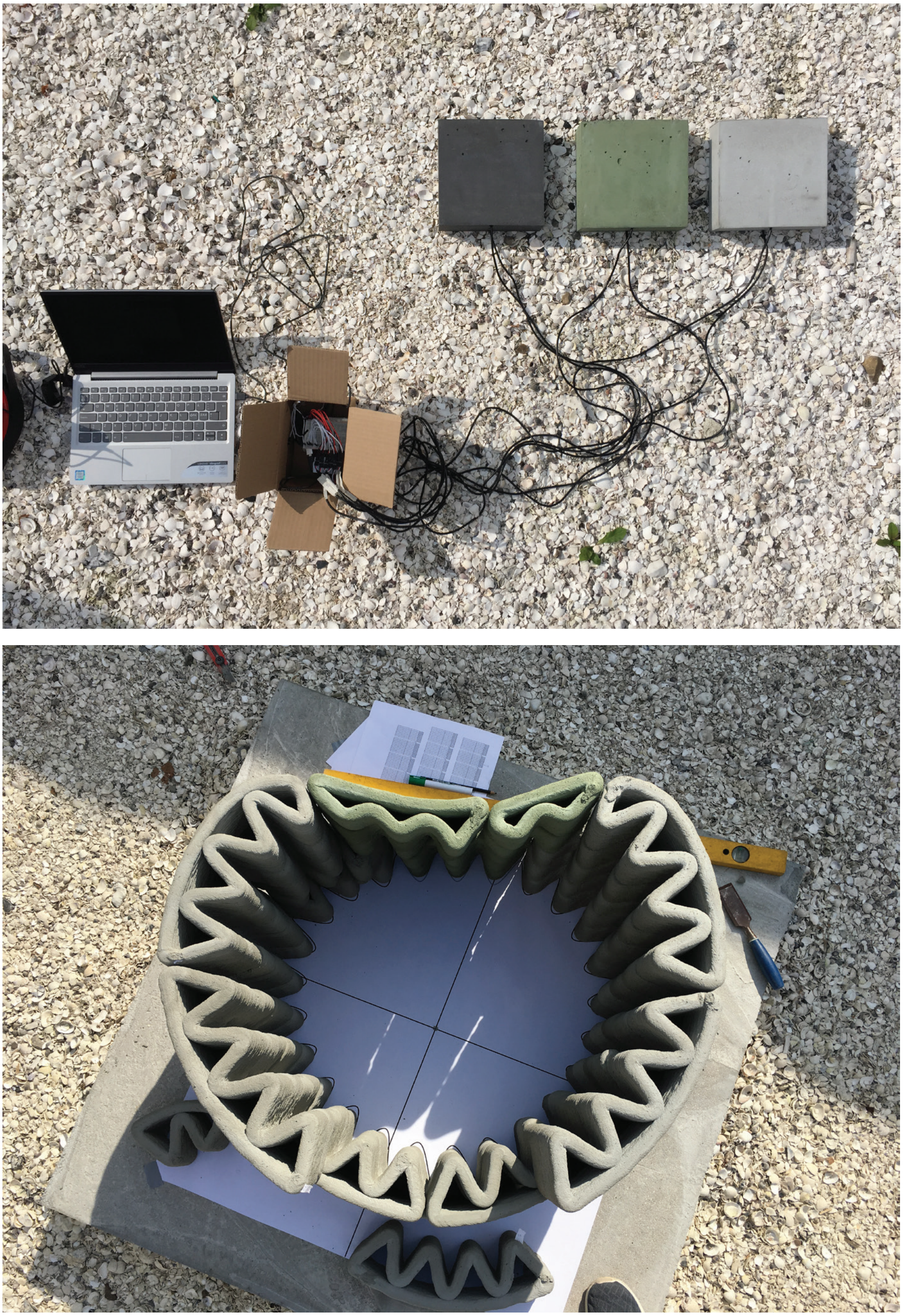


Figure 4.6.
Top: Recording of thermal data to inform the computational simulation of surface temperature buildup.
Bottom: Top-view of the full-scale demonstrator showing the variations in local surface undulation.
Photos by Isak Worre Foged and Mads Brath Jensen

robotic fabrication, along with a computational simulation of the involved robotic processes, the design exploration can actively engage with both digital and physical design investigations – accumulating and implementing valuable information from both domains. This approach leads to a broadening of the architect's field of work to design not only the architectural object but also the system/process/tool that generates the architectural object and the system/process/tool that fabricates the architectural object. A robotic approach where design and fabrication activities run in parallel also allows for addressing the conundrum of time and uncertainty and deal with the risk that "*emerge when design decisions are made without being able to anticipate the constraints of the future implementation phase*" (Bechthold, 2018). However, it is crucial to remember that although a robotic-driven and parametric design exploration allows for the discovery of design- and fabrication-related constraints, it also entails a more elaborate definition of the problem space involving a broad set of interrelated restrictions and multiple performance criteria. During the study, the exploration of this complex problem-solution space was accomplished through the implementation of a search algorithm. Using the internal Grasshopper component Galapagos, the computational framework facilitated an automated evolutionary search procedure that explored solutions within the parametrically defined design/search space.

Non-deterministic design exploration

Through implementation and execution of the robotic-based design exploration, the study revealed that while the computational design framework allowed for a (to some degree) free and non-deterministic design process the robotic-based design framework, on the other hand, was considerably more restricted and deterministic. For the advancement of robotic-based design exploration and in particular, the implementation of robotic fabrication processes within the early design phase, attaining an open-ended, creative and non-deterministic process is crucial. Based on the design process conducted in this experiment, the study finds that human interaction with the robotic fabrication setup and -process is restricted and that this is caused by the method applied for generating and structuring fabrication data and the file-based transferring of this data from the computational design framework to the robotic system. The generation of start-to-end robotic control code along with the file-to-factory approach for data transferal leaves very little room for making changes on-the-fly or introducing alternative fabrication steps. During the fabrication processes, this resulted in passive periods with the human agent standing on the sideline as a mere spectator. Exploring alternative ways of transferring or streaming successive sequences of the entire robotic program holds great potential for human interaction within a non-deterministic fabrication process.

Additionally, the choice of material system also has an impact on the manoeuvrability of the ongoing fabrication process. The time-dependent chemical process involved in the extrusion of concrete material set a very tangible restriction on the fabrication process. Along with time-consuming preparations of the extrusion system and tedious post-fabrication cleaning processes, the properties of the material system, and how it is configured has a significant impact on the interactions it affords.

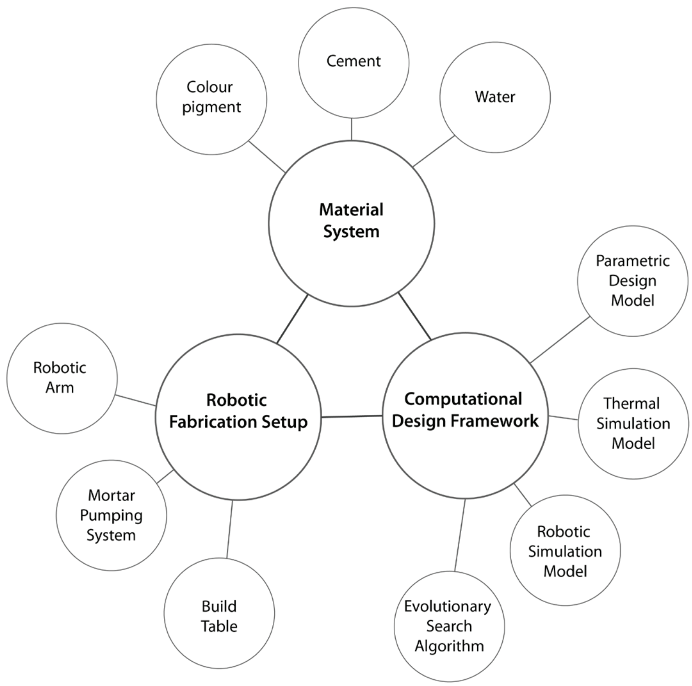


Figure 4.7.
Schematic overview of the Robotic-based Design Framework.
Diagram by Mads Brath Jensen.

Creative implications of robotic fabrication

The study sought to investigate the potentials of, and requirements for, integrating robotic fabrication in a computational-based design process. As previously mentioned, the integration of robotic fabrication has implications for the development of the computational design framework and the methods needed to establish this. The implementation also requires a re-thinking or re-structuring of the design process itself – involving a parallel exploration of both physical material/fabrication processes and computational simulation-driven performance criteria. The iterative process of acquiring knowledge through physical and computational design explorations and translating this into parametric design parameters/restrictions has a profound impact on the creative and cognitive processes. From one perspective the continuous parametric 'recording' of design restrictions and intentions can help free up the cognitive load of the architect, but navigating the increasingly complex parametric network can also be a mental strain that inhibits a creative flow.

The study mainly involves an exploration of two distinct scenarios; designing and exploring the design framework and exploring designs with the design framework. To examine the impact of integrating robotic fabrication in a computational-based design process, it could be an advantage to apply a separate focus and explore in isolation how the design framework affords exploration of design output. Additionally, this approach allows for an investigation of the usability and adaptability of the robotic framework when applied by non-experts, as this user group has not yet acquired the skills and competencies to create and explore a robotic design framework.

4.3 Design Study 2: Robotic Wood Milling

4.3.1 Introduction

The findings of the previous study showed that the integration of geometric shape generation, thermal simulation, genetic search algorithms, and robotic simulation and fabrication allowed for an iterative and explorative design process closely tied to, and informed by, material-based prototyping. Internalising geometric relations, material properties and fabrication constraints within a computational design model allow for a precise description and bridging between the two fields of the problem-solution space, making it possible to search large design spaces for viable and optimal solutions. Although the establishment of relations between selected design parameters allows for the construction and management of complex design systems the previous study also suggests that this shift from designing objects to designing system that generate objects, entails a requirement for a new set of technical and software-based skills for the architect. The previous study also revealed that the internal complexity of the investigated material system, as well as the associated fabrication process, has a vital impact on the operation and flexibility of the established design process. It is, therefore, in this second study, appropriate to introduce a different material system to examine and compare the role and influence on the afforded design process.

The background on previous solutions stems from the findings of the previous chapter. Further, it includes recent work by Reinhardt et al. (Reinhardt *et al.*, 2016) into the combination of acoustic simulation and robotic fabrication, as well as the studies by Foged et al. (Foged, Pasold and Jensen, 2014) investigating the combination of acoustic simulation, parametric modelling, and evolutionary search algorithms. The integration of parametric design tools and digital fabrication techniques for the construction of the sound-diffusing panels for the large concert hall of the Elbphilharmonie in Hamburg, designed by Herzog de Meuron, shows a large scale application of these design-, simulation-, and fabrication methodologies. Trough parametric control of a sound-diffusing pattern consisting of more than a million individually shaped cells the custom design system allowed for a bitmap-driven exploration of design variations and the subsequent automated planning and CNC milling of approximately 10,000 gypsum fiberboard panels (Koren and Müller, 2017). The subtractive technique of CNC milling has been further explored in work carried out by the interdisciplinary research project Robotic Woodcraft. In their work they explore robotic wood milling, along with other techniques as precise placement, drilling, and cutting of wood objects, thereby displaying the creative potential of treating industrial robots as integral design tools and the effects of both designing and controlling the entire robotic fabrication process (Santorso *et al.*, 2017).

The background on potential solutions is the integration of acoustic simulation and robotic-based milling procedures in a computational design framework. A second aspect is the impact that an application of this proposed framework has on the design process for non-expert designers.

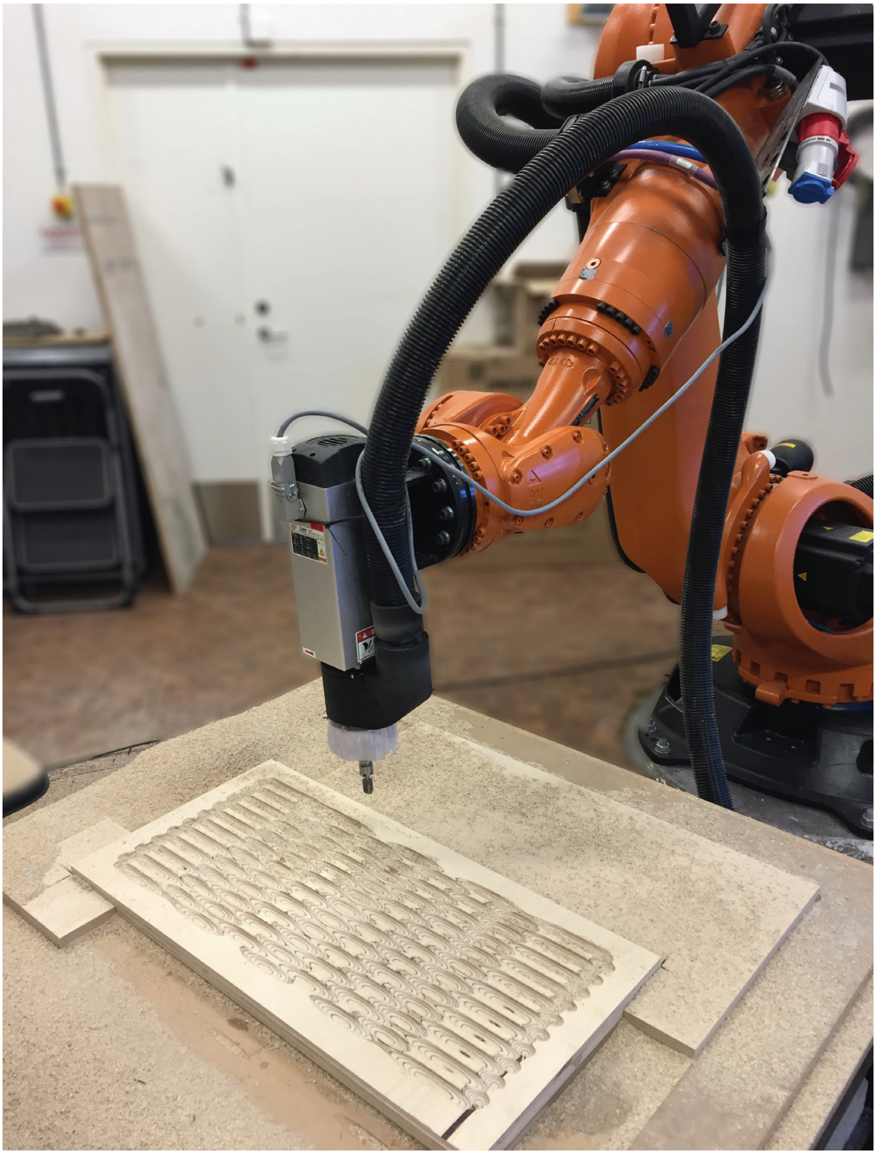


Figure 4.8.
Robotic milling of prototype for acoustic panel. Photograph by Jacob Hilmer. (Appendix B)

The study attempts to construct a robotic-based design framework that supports a parallel exploration of acoustic performance, robotic milling techniques, material performance and spatial features. The study also seeks to capture and examine the creative and cognitive processes that arise when non-expert designers are exposed to a pre-established robotic-based design framework.

The study presents a design framework consisting of a parametric design model, an acoustic simulation model, and a robotic simulation model. The study also describes the setup of a design studio conducted with students on an architectural master level with the aim of implementing and applying the proposed design framework. Selected student work together with a final 1:1 prototype of a mobile library structure serves to showcase the resulting design process, and the study concludes by discussing the impact that the robotic-based design framework has on the creative and cognitive processes of non-expert designers.

The study has been disseminated through the journal paper "Robotic Fabrication of Acoustic Geometries – an explorative and creative design process within an educational context" ('Paper 2' in Appendix B). The focus and scope of this journal paper allowed thorough dissemination of the applied methods, the associated results, conclusions, and relevant topics for discussion. Therefore, the following section contains a brief addition to the discussion of the project, describing the gap still existing between the creative design phase and robotic fabrication.

4.3.2 Discussion

The discussion chapter in 'Paper 2' is concerned with several issues uncovered during the preparations for and completion of the three-week robotic-based design studio. However, one crucial aspect needs to be included in the discussion of the study.

The process of fabricating the students' final (and first) prototype revealed the gap that still existed between the creative design phase, in which the students were in a mode of open-ended and feedback-driven interaction with the computational design system, and the robotic fabrication phase, where the students are placed in a passive 'spectator' mode standing on the 'sideline' while a set of predetermined actions are executed during the automated process. As the study uses robotic wood milling as fabrication process (see figure 4.8) safety restrictions does not permit the presence of people within proximity to the robotic arm, thereby making direct interaction impossible. Even if the robotic end-effector were substituted for a far less dangerous type, security protocols for the robotic arm itself would hinder most interactive or collaborative processes. Another aspect that needs to be overcome in the move towards integration of more creative and open-ended robotic fabrication processes is a more fluent and continuous exchange of information between the design framework and robotic fabrication setup – "*Byte to Robot rather than File to Factory*" (Johns, Kilian and Foley, 2014). The use of pre-defined programs, with complete instructions for robotic fabrication processes, must be substituted with a continuous exchange of fragmented instructions – thereby allowing for human input during the robotic-based fabrication process. Breaking up the otherwise predeter-

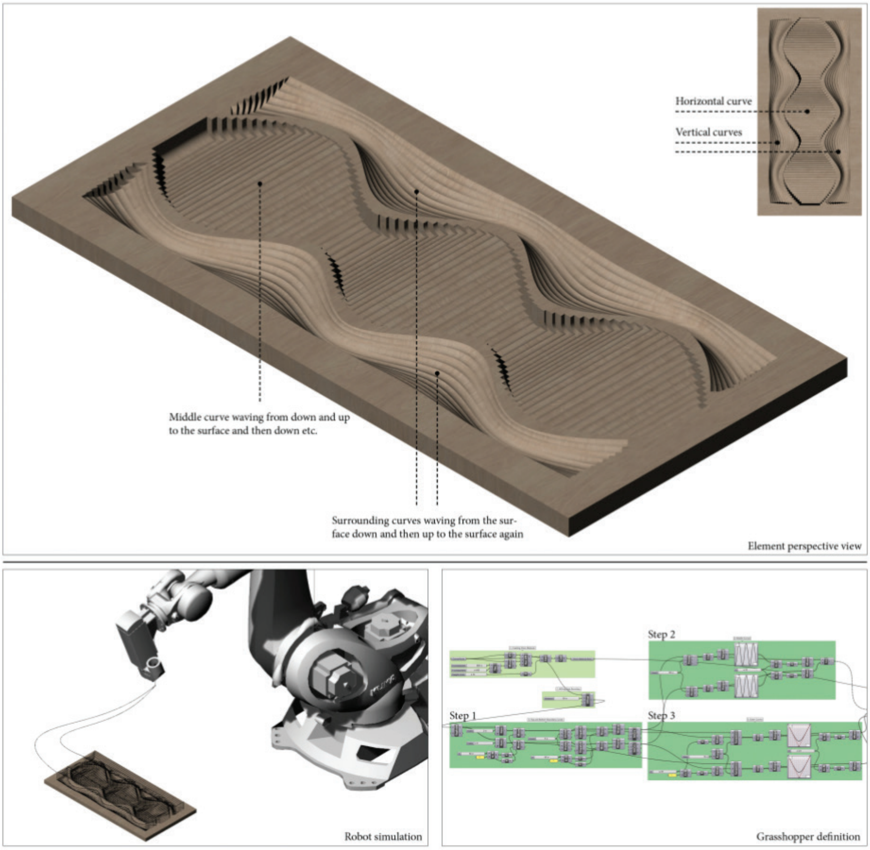


Figure 4.9.
Image showing a parametric design system (bottom right), with one out of many possible geometric compositions (top) and the corresponding simulation of the robotic fabrication. Visualisation by student Maria Møller Salling. (Appendix B)

mined fabrication process supports a more flexible and dynamic approach to robotic fabrication, allowing for a more explorative and less determined transition between the design and fabrication phase.

4.4 Collected Findings and Discussion

The two studies presented in this chapter, and disseminated through 'Paper 1' and 'Paper 2' respectively, seek to unfold the potential impact of implementing robotic fabrication into a computational-driven design process. Both experiments approach the investigation through the development of a robotic-based design framework that combines a robotic fabrication system, a computational framework, and a material system. The software environment of Rhino/Grasshopper, allowing a parametric approach to the design of the computational framework, is used in both studies as it supports the implementation and adaptation of existing methods for generation of geometric solutions, environmental simulation and robot simulation/control, as can be seen in figure 4.9.

Expert and novice designers

The method and the scope for investigating the research field do however differ between the two; with the first experiment investigating the parallel and iterative process of developing a robotic-based design framework and designing with the robotic-based design framework, and the second experiment shifting the focus towards non-expert designers' use of a pre-established robotic-based design framework. The results of the first study thereby rely solely on the documentation and evaluation of the author's design process, whereas the second study places the author in the background and evaluates the conducted design process based on test subjects. This shift in research method allows the thesis to obtain two different angles on the research subject and compare the findings.

The implementation of an evolutionary algorithm in the first experiment allows for an automated search within the gradually extended parameter space. Applying this search method allows for an examination of a vast solution space in limited time, but although this method is easily accessible through Grasshopper component like Galapagos (many other similar components does exist) the usefulness of the results highly depends on the combination of the parameter space configuration and the choice of performance criteria (Stasiuk, 2019). Therefore, even though the search method is found to be of great benefit in the first experiment, the computational framework adopted by the students in the second experiment does not contain an automated search method. Instead, the students are asked to continuously and through a manual process, perform a systematic search of their established solution space.

Importance of the Material System

To understand the implications that the type of material system, and the accompanied fabrication process, have on the implementation of a robotic-based design framework and design process, the two studies employed an additive concrete

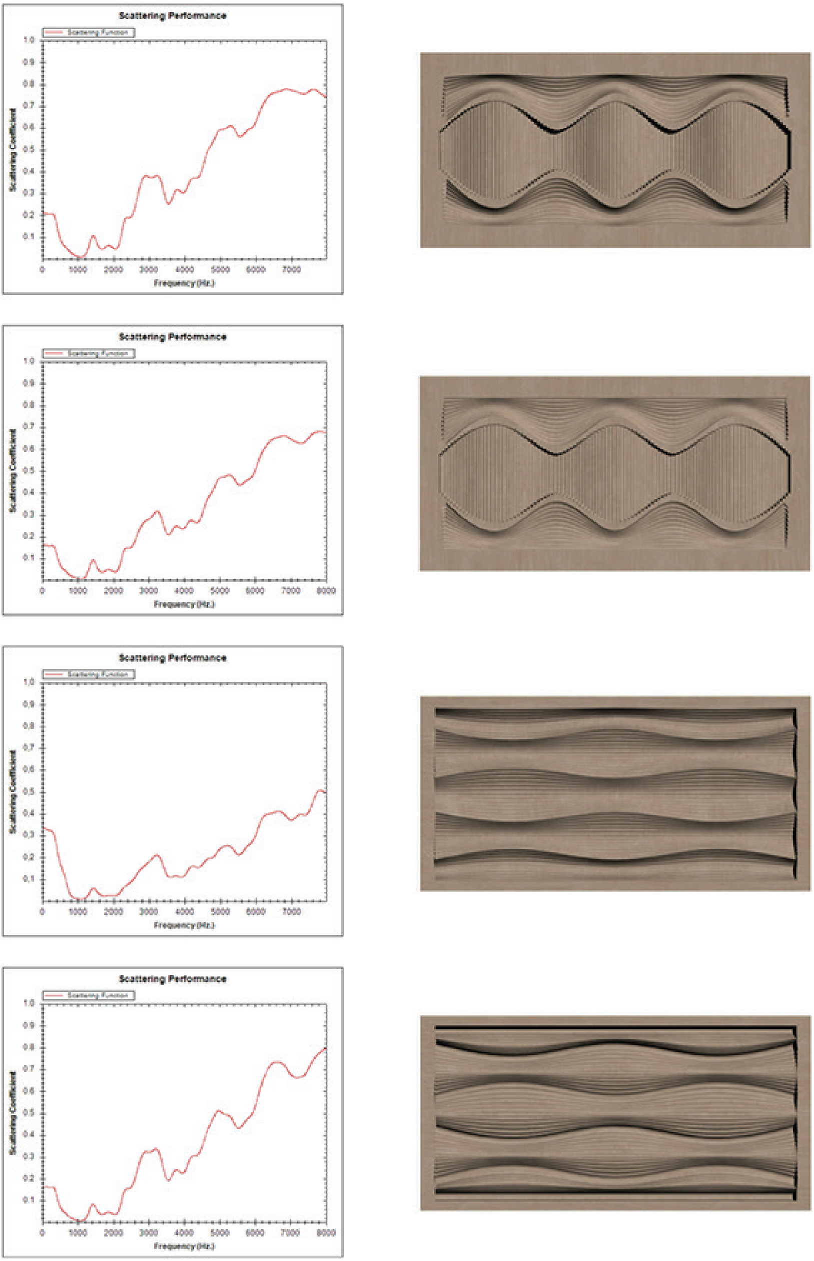


Figure 4.10.
Image showing the acoustic performance (scattering values) of the corresponding geometrical composition. Visualisation by student Maria Møller Salling. (Appendix B)

printing process and a subtractive wood milling process. The studies found that the material system has a significant impact on the design framework's capacity to support a creative design process. The time-dependent and irreversible hardening process of the mixed concrete, used in the first study, sets a very fixed scope on the fabrication process and to some degree demands a well-prepared and very deterministic set of premade robotic instructions that ensure effective use of the available fabrication time. The concrete-based material system reinforces the gap between the non-deterministic creative design process and the, in this case, fully deterministic fabrication process. For the second study, it is to a lesser extent the wood-based material system itself that restricts the creative design process, as it is the planning of the 3-week architectural studio and its limitation of only allowing students the robotic fabrication of a single prototype in the final days. Leaving the constraining effect regarding the planning of the studio out of the account, the wood-based material system does have the ability to support a much more simultaneous and interlaced design- and fabrication process. The wood-based material system does not involve a time-dependent material process, and the robotic-based milling procedure can quickly be interrupted and reinitiated based on new design inputs. Naturally, the subtractive method of wood milling is not reversible, which sets some restrictions on the introduction of new design intentions during the fabrication process.

Creativity in Human-Robot Design Exploration

For both studies, the development and implementation of a robotic-based design framework were aimed at the investigation of creativity during explorative design processes. Whereas the setup of the first study permitted modification of the entire design-to-fabrication process, involving both the design of the computational design framework, the robotic fabrication system, and exploration of the design object itself, the second study was limited to exploring the design object within a fixed computational design framework and a pre-configured robotic fabrication system. This difference in scope, together with the fact that the first design process was run by the author and the second study with students, naturally affected the possibility of investigating creativity across the human-material-robot design space. Consequently, the second study didn't result in the finding of creative processes associated with the physical robotic milling of wood elements or within the interaction between human and robot. The second study did, however, find that the computational design framework supported a highly iterative and explorative design process in which the simulation of robotic fabrication played an active and design-informing role. The students, especially the individuals capable of overcoming the technical challenges of parametric modelling and acoustic simulation, were found to perform creatively during these computational design processes.

However, during the first study, the robotic-based fabrication processes allowed testing and critical evaluation of both the fabrication process, the material behaviour and the resulting physical prototype. The robotic fabrication phase also permitted verification regarding the credibility of the computational simulation as well as observation of new material phenomena during robotic fabrication. Similar to the

Figure 4.11.
Physical measurements of the acoustic performance were performed on varying configurations of the students' milled plywood prototypes. Photo by Isak W. Foged. (Appendix B)

second study, the occurrence of creative design exploration was almost limited to the computational design processes, where problems and solutions were explored through fast iterations based on both aesthetic-, acoustic- and fabrication-driven performance criteria. An example of the acoustic-driven design variations is visualised in figure 4.10. Although the first study encompassed exploration of the complete robotic-based design framework, only in a few cases, related to the exploration of fabrication variables (such as nozzle sizes, extrusion paths, and layer/element heights) and their impact on design outcome, did creativity occur in relation to robotic fabrication. Mostly, the phases of robotic fabrication dealt with the verification of already simulated outcomes.

Solutions for better integration of human-material-robot processes have been uncovered through the completion of the two studies. The properties of the chosen material system is a crucial aspect for the scope of the following design explorations; to allow for increased interactions between human and robot the study finds that a material system that suits the abilities and constraints of both the human co-worker and the robotic fabricator is critical. A material system that allows human and robot fabrication to co-occur might be the key to human-robot co-fabrication. Another critical element is an investigation of methods and techniques for circumventing the use of predetermined fabrication data as this only permits a fixed and unchangeable fabrication process. Exploring methods that decompose this robotic process and allow for in-fabrication design intervention to occur is necessary. And at last, successfully establishing non-deterministic approaches to human-robot co-fabrication emphasise the importance of methods and techniques for the computational framework to process design input during co-fabrication and ways in which human and robot can communicate and interact.

References

Bechthold, M. (2018) “Real-time Robotics,” in Dass, M. and Wit, A. J. (eds) *Towards a Robotic Architecture*. Novato, CA: Applied Research and Design Publishing, pp. 114–125.

Brell-Çokcan, S. and Braumann, J. (2010) “A New Parametric Design Tool for Robot Milling,” *Proceedings of the 30th Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA)*, pp. 357–363.

Foged, I. W. (2013) “Architectural Thermal Forms,” in *Proceedings of the 31st eCAADe Conference*. Delft, pp. 99–105. Available at: http://cumincad.scix.net/cgi-bin/works/Show?ecaade2013_032.

Foged, I. W. and Jensen, M. B. (2018) “Thermal Compositions Through Robot Based Thermal Mass Distribution,” in *Computing for a better tomorrow - Proceedings of the 36th eCAADe Conference*, pp. 783–790.

Foged, I. W., Pasold, A. and Jensen, M. B. (2014) “Evolution of an Instrumental Architecture,” in *Fusion - Proceedings of the 32nd eCAADe Conference*, pp. 365–372. Available at: www.create.aau.dk.

Hauberg, J. (2011) “Research by design: a research strategy,” *Architecture & Education Journal*, 1(2), pp. 1–11. Available at: http://recil.ulusofona.pt/handle/10437/2043.

Johns, R. L., Kilian, A. and Foley, N. (2014) “Design Approaches Through Augmented Materiality and Embodied Computation,” in *Robotic Fabrication in Architecture, Art and Design 2014*. Cham: Springer International Publishing, pp. 319–332. doi: 10.1007/978-3-319-04663-1_22.

Koren, B. S. and Müller, T. (2017) “Digital Fabrication of Non-Standard Sound-Diffusion Panels in the large

Hall of the Elbphilharmonie," in Menges, A. et al. (eds) *Fabricate 2017*. UCL Press, pp. 122–129.

Reinhardt, D. *et al.* (2016) "Towards a Micro Design of Acoustic Surfaces," in *Robotic Fabrication in Architecture Art and Design 2016*, pp. 136–149. doi: 10.1007/978-3-319-26378-6.

Santorso, K. *et al.* (eds) (2017) *Robotic Woodcraft - Towards the Craftmanship of the Future*. Vienna: University of applied Arts Vienna. Available at: http://www.roboticwoodcraft.com/wp-content/uploads/2019/04/RoboticWoodcraft.pdf.

Stasiuk, D. (2019) *Adaptive Parameterisation: Methods for employing flexible data structures for complex modelling practices in architectural design*.

5.

Interactive Robotic Design Exploration

5.1 Design Study 3: Robotic Brick Stacking I

5.1.1 Introduction

In the previous chapter, the two design studies showed that the implementation of robotic fabrication allows for a design process informed by both computational simulations of robotic fabrication and physical robotic-based fabrication of material prototypes. Through progressive exploration, new insights in the form of constraints and opportunities can be elicited and used to establish relationships that 'bridge' the domain of design exploration with that of robotic fabrication. The studies showed that the computational design framework supports the management of this growing web of relations and allows for an exploration and evaluation (simulation) of the problem-solution space it defines.

The previous studies identified a gap between the indeterministic creative process, taking place during the computational-based design exploration, and the deterministic process of robotic fabrication. Several aspects were identified as the likely reasons for this very apparent difference in creative potential. One aspect is the fabrication processes linked to the chosen material system and their openness towards human interference. The time expenditure associated with concrete extrusion and the security risks tied to high-speed milling processes did not allow for any human intervention during robotic fabrication, thereby excluding any spontaneous creative input. A second aspect lies in the fact that running pre-determined robotic programs that contain the complete definition of all consecutive actions needed to complete the fabrication process from start to finish, renders all interaction impossible. Decomposing or fragmenting the series of robotic commands could allow for creative design interventions to occur during robotic fabrication. Furthermore, the two studies did not succeed in seeing the human as a co-worker and therefore, did not include any tasks suitable for human capabilities, an element that should be addressed in future work.

To accommodate the challenges associated with the selection of a suitable material system, the following two design studies incorporate bricks of varying material composition. Bricks, due to their clear geometric definition are very generic building elements that allow for a high degree of freedom and allows assembly into an almost unlimited number of configurations (Foged *et al.*, 2016). The brick, through its versatility, its alignment with the human scale, and its repetitive fabrication format, lends itself particularly well to assembly processes by both the human hand and robotic processes. Following traditional brickwork, with its simple vertical stacking, the brick system also has the option of assuming both a fixed or a reversible configuration by adding mortar or adhesive or merely leaving it out.

The study has been disseminated through the book chapter "Acoustic Wall: Computational and Robotic Design Integration of Four Primary Generators" (Appendix C), referred to as 'Paper 3'. As can be deduced from the chapter's title the focus of the publication was how an integrated framework featuring acoustic simulation, computational design and robotic fabrication could support the exploration of four primary

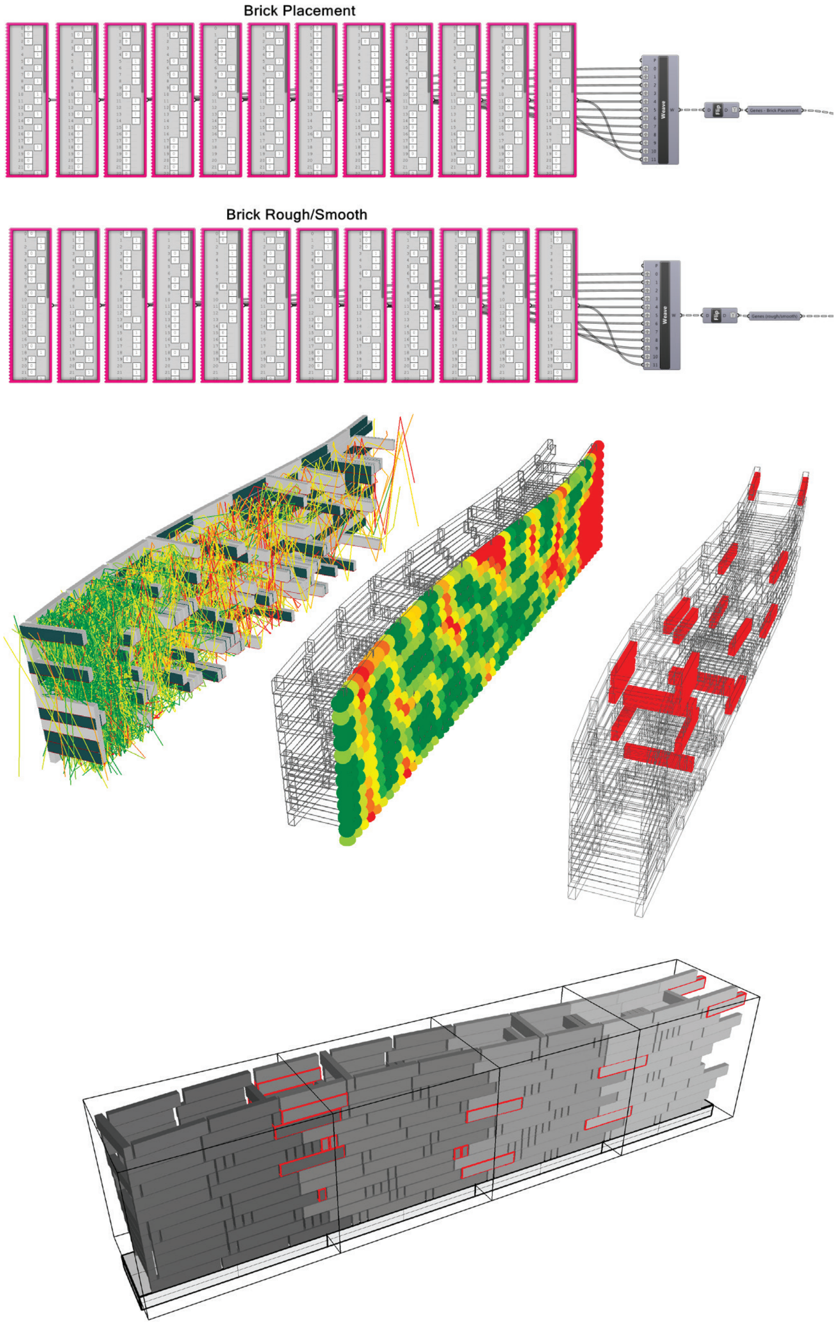


Figure 5.1.
Visualization of the genetic search displaying gene-composition, performance criteria (acoustics, binder brick distribution, and un-supported bricks) and the final fabrication setup divided into four separate modules. Illustration by Mads Brath Jensen

generators; optics, acoustics, robotics and statics. To better trace the advancement of the proposed robotic-based design framework, the methods, results and discussion receive further elaboration in the following paragraphs.

5.1.2 Methods

The Computational Design Framework

As described in 'Paper 3', the computational framework is based on the parametric CAD environment Rhino/Grasshopper by McNeel Inc., allowing integration of both robotic simulation and control using KUKA|prc, developed by Johannes Braumann; Pachyderm Acoustics, developed by Arthur van Harten; Goat, developed by Rechenraum; and bespoke Python-coded GH-components to support instability tests, developed by the authors of 'Paper 3'.

Similar to the two previous studies, the computational design framework applied in this study consisted of several clusters (or sub-systems) that take care of each their unique task. The clusters were named: design generation, acoustic simulation, structural analysis, robotic simulation, and performance search.

The design generation cluster allowed the design of a double-sided wall structure connected with 'binder bricks' for ensuring structural stability of the slender walls. A lofted surface, based on two guide curves, defines the shape of the brick wall and through horizontal planar intersections of the surface, a set of layer curves are defined. The layer curves guide the location and orientation of the brick geometries. A pattern generator consisting of variable Boolean values informs the orientation of each consecutive brick; either parallel to the layer curve (resulting in a regular brick) or orthogonal to it (resulting in a binder brick). Another pattern generator controls the orientation of the rough side of the bricks, thereby directly informing the visual expression and acoustic performance of the wall (see figure 5.1).

The acoustic simulation cluster *"… applied the Pachyderm acoustic simulation software into the parametric model, and describe each material element through geometric, material absorption and scattering coefficients*" (Appendix C). With the limestone wall intended for occupying a small exhibition room, for which the interior composition and location of the wall was unknown, the acoustic performance dealt with optimisation of the sound-energy distribution through the inside of the wall assembly.

The structural analysis cluster examined the brick wall's ability to structurally support each new brick addition throughout the complete robotic stacking process. This analysis was achieved with a custom python component that calculated the location of a brick's centre of gravity and compared it to the collective area of the supporting surfaces (the top surface of the bricks in the previous layer). If the centre of gravity lies outside the calculated area of support the brick would topple when placed by the robot and the brick is therefore marked as 'not stackable' and graphically highlighted during the structural analysis process. The structural analysis also measured the internal distance between all 'binder bricks' to inform about the distribution and

Figure 5.2.
The limestone brick wall was produced as four seperate section. Here two of the sections are being joined together. Photo by Isak W. Foged.

density of these bricks, thereby offering insights regarding the structural interlinking between the two, by themselves, unstable wall elements.

The cluster for robotic simulation and control contained a parametric definition of a pick-and-place procedure that allowed for individual placement and orientation of each brick in the designed wall structure. The output of the robotic simulation components supplies feedback on the robots ability to reach all the brick locations, informing the division of the wall into smaller buildable elements. In the performance search cluster, an evolutionary search engine (Galapagos) is implemented to investigate the solution space using performance criteria related to increased structural stability and sound transfer through the wall. Design restrictions related to the geometric freedom of the guide surface, directly controlling the curvature and displacement of the brick wall, was informed by several physical design tests with both scaled and real-sized bricks.

The arrangement and connection between these clusters establish a computational design framework that seeks to support a parallel and near simultaneous exploration of several design aspects. Hence, the parametric setup allows for manual manipulation of the design variables, with subsequent visualisation of the effects this has on the established performance criteria, but the setup also permits the designer to initiate an automated genetic-based search.

Material System

The discussion in the previous chapter, regarding the impact and complexities of the applied material systems, was accommodated in this study through the implementation of a simple, reversible and timewise indifferent material system consisting of pre-cut 30 x 60 x 300 mm limestone bricks, as seen in figure 5.2. As mentioned in 'Paper 3', these bricks were: *"…assembled into a sound-distributing double-layered wall with cross binders. Each limestone brick consisted of one rough side and five smooth sides, which acted as material variables in the search for a limestone wall composition that satisfied project-specific acoustic, structural and expressive characteristics*" (Appendix C). Contrary to the two previous studies, this material system allowed for both human and robotic assembly, and only when applying glue between the bricks, as done during the assembly of the final demonstrator, does the material system achieve a non-reversible state.

The material system affords a sequential stacking of bricks performed to very high precision by the robotic arm, while simultaneously allowing a human co-worker to participate, although with less precision. The material system thereby supports a design process that allows a parallel exploration of the given problem-solution space and takes advantage of both a human co-worker with great adaptation and less precision and a robotic arm with high precision and very little adaptation.

The logistic setup of the study, with the design process and final fabrication taking place in Denmark and Turkey respectively, entailed that the limestone material was only available for the fabrication of the final 1:1 demonstrator. For this reason, the initial experiments were conducted with plywood bricks of the same dimensions. As

Figure 5.3.
The interior composition of the limestone brick wall. Photo by Mads Brath Jensen

the robotic fabrication process didn't include any manipulation of the material, but merely a reposition of geometrically simple objects, the wood-based bricks acted as an efficient substitute.

Robotic Setup

To obtain structural stability for the final demonstrator glue was applied as a bonding agent between every horizontal layer of bricks. To allow for an investigation of more interactive processes of human-material-robot processes during the explorative design phase, this study did not pursue the development of a glue-dispensing end effector for the robotic arm but instead saw this as the opportunity to introduce a human co-worker and establish a means for human-robot communication. To facilitate an investigation of this collaborative fabrication process, in which work is shared between a brick stacking robotic arm and a glue-dispensing human co-worker, the study implemented a gesturing system using the Leap Motion sensor, as seen in figure 5.5. The gesturing system, using a simple method for tracking the orientation of hand(s) and counting of fingers, was integrated into the computational design framework and permitted control/triggering of specific fabrication processes. To verify that the sensor received correct gestures, a single-line LCD, controlled by an Arduino Uno board, was implemented. Another communication system, in the form of a simple push-button, was installed to accomplish the same task, but more directly.

As in the case of the availability of limestone material, the logistic setup also required the robotic prototyping process to be conducted with a different robotic arm, a KUKA KR300-R2500. This allowed the study also to investigate the process of communicating and converting design and fabrication data between two distant locations with each their robotic fabrication setup.

5.1.3 Results

The 'Results and Discussion' section in 'Paper 3' presented four main findings of the conducted study: the ability to integrate the four primary generators in the computational design model; the possibility for human steering interventions during computational search processes; the uncertainties connected to hand-gesturing for human-robot communication; and the need for human intervention during robotic fabrication to allow for necessary changes and incorporate new design intent.

In addition to these results, the robotic-based design framework, covering both the computational design framework, the robotic system, and the material system, also supported a smooth and integrated design exploration featuring a positive shifting between physical and computational design exploration. The design framework thereby supported a parallel design exploration of several primary generators - continuously re-informing the problem-solution space.

The robotic-based design framework, containing an integrated network of models for both design, analysis, solution-search, and robotic fabrication, allowed for both design exploration and final fabrication of a double-layered limestone brick wall, as seen in figure 5.3. The parametric design framework allowed for easy communication

Figure 5.4.
Robotic fabrication process in Istanbul. The bottom row shows the robotic gesturing during the human-robot co-fabrication, starting with the robot gesturing the intended location of the brick, the robot then moves away to allow for the gluing process, finally the robot places the brick and continues to pick-up the next brick.
Photos by Burcu Bicer Saner.

and adaptation of fabrication instructions between two remote locations with two differing robotic setups.

5.1.4 Discussion

As mentioned above the discussion of the study presented in 'Paper 3' only briefly touch upon four main findings. To clarify these findings and support the trajectory of the following design studies, a more in-depth discussion is presented below.

The computational design framework

The structure of the computational design framework, as described in the 'Methods' section above, is based on an adaptation of the computational design frameworks developed during the first two studies, presented in chapter 4. As mentioned in the 'Results and Discussion' section in 'Paper 3' the computational design framework contained a two-phase stochastic and deterministic search procedure to enable a search for design convergence based on multiple primary performance criteria. The deterministic search often involved a manual exploration of the established design restrictions, changing and re-framing the problem-solution space, while the automated stochastic search involved a search for solutions within a fixed problem-solution space. The study found that the deterministic search procedure was often initiated based on new design intentions or restriction discovered during physical prototyping (with or without robotic assistance). And, that the resulting re-framing of design restrictions were followed by a stochastic search for high performing solution within this updated problem-solution space. This dynamic process of freely switching between both the physical and digital realm, as well as between deterministic, non-deterministic, and stochastic design exploration/search, allows for an increasingly integrated design process that supports the design of novel structures. To improve such robotic-based design explorations, it is crucial to further investigate the behaviour related to the switching between these different modes of designing and to understand how a robotic-based design framework can better support the quality of the design exploration and the resulting design output.

By considering the designer an active element in the computational design and robotic fabrication loop, the study sought to facilitate a smoother transition between computational- and robotic-based design exploration. Integrating aspects of human-robot co-fabrication the computational design framework could intentionally leave specific fabrication procedures undetermined or unsolved, for instance, due to the complexity and time involved in parametrically solving a specific task, and allow these to be solved or completed by a human co-worker. An example of this human-robot co-fabrication can be found in the way that the study approached the application of glue. Rather than aiming for a fully automatic robot-based solution, the computational design framework was extended with a procedure that incorporated co-fabrication. As visualised in figure 5.4 the robotic arm would gesture the position of the new brick, and through that specify the area needing glue, move the brick away to leave room for the glueing procedure, and move back again to place the brick on the target location. The push-button triggered the alternation between

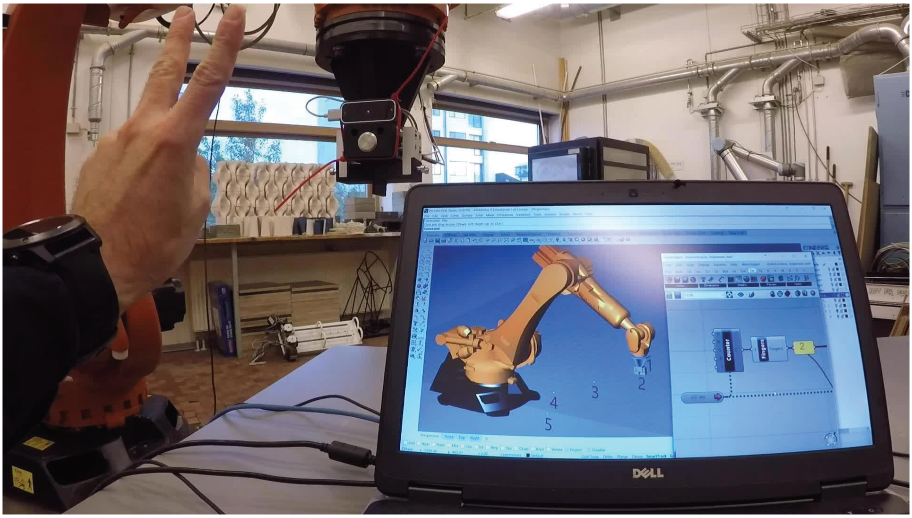


Figure 5.5.
Initial experiment with recognition of hand gestures for controlling robotmovements through a setup consisting of a Leap Motion Sensor and Rhino/Grasshopper.
Photo by Mads Brath Jensen.

robot and human action. Another scenario of this co-fabrication can be found in the insertion of temporary support bricks during the fabrication process. Again, instead of solving what would most likely be seen as an error in the generation of the brick wall, in this case the existence of unsupported bricks, the problem was approached by graphically visualising the unsupported bricks. The approach thereby allowed the human co-worker to take appropriate action during placing of the bricks. While this approach would not be viable for robotic fabrication of structures in the building industry, which would demand full automation, these 'shortcomings' in the fabrication system can be seen as an invitation for creative co-fabrication during a robotic-based design exploration.

The parallel development and utilisation of the computational design framework focused on supporting an explorative and creative design process taking advantage of the potentials of robotic fabrication. The integration of both design and fabrication model within an interrelated parametric framework allowed for a new approach towards the communication of fabrication data between designer and fabricator. The communication involved no technical drawings and no pre-determined production file, but instead a computational framework – a 'fabrication generator' – that given information regarding the current robotic fabrication setup (incl. robot type, stacking area, brick feeding area), would generate the robot program needed for fabrication of the desired brick wall. Reflecting on these aspects of the study, a minimum of additional information regarding the robotic fabrication process was needed in the transition from design exploration in Aalborg, Denmark to robotic fabrication of the brick wall in Istanbul (Turkey), although the two partners never physically met or received much information regarding the context of the robotic fabrication setup. The simple robotic gestures supporting the human-robot co-fabrication, along with the graphical communication of unsupported bricks, prevented uncertainties during fabrication in Istanbul and resulted in a more or less flawless human-robot fabrication process.

Interactive Human-Robot Fabrication

As previously mentioned the study was carried out across two different geographical locations (Aalborg and Istanbul), with each their differing setup for robotic fabrication, and with the desired limestone material only being available in Istanbul where final fabrication and subsequent exhibition were to take place. The design phase, conducted with the robotic setup in Aalborg, explored techniques and methods for human-robot interaction through implementation of the Leap Motion sensor for hand-gesture recognition, as seen in figure 5.5. The implementation of gesture control allowed the counting of fingers to be used as a numeric variable for triggering various actions in the computational design framework. One method was to connect a specific finger-count to a Boolean value that triggered a specific IO in the robot. This method included a 'Wait for IO' in the robot program telling the robot, at a specific location in time, to wait for a 'True' value triggered by for instance the recognition of precisely two fingers. During the explorative design phase, the gesture-based interaction with the robot allowed for simple communication of selecting between two types of bricks or choosing whether to flip the orientation of the brick around its vertical axis thereby orienting either the smooth or rough side of the brick outwards. The gesture system was also used during the manual application of glue, where a gesture would inform the robot about the completion of this process and thereby acknowledge that the fabrication process could resume. During later stages of the design phase, and also during the final fabrication in Istanbul, the gesture system was abandoned due to the tedious process of passing a sign, getting clear feedback/ cues about the sign being received correctly by the system, and then finally acknowledging this feedback with another hand sign. Instead, the same result of pausing/ resuming the fabrication process to allow for safe human interaction was achieved through the robot's teach pendant and manually running the robot program in the safety mode 'T1'.

Based on a parallel robotic fabrication of physical prototypes and computational simulation of robotic control, structural stability, and acoustic performance, the robotic-based design exploration revealed essential aspects for future work with interactive robotic-based design exploration. Compared to the two previous design studies, using concrete extrusion and wood milling as fabrication method, this study, through the well-known method of brick stacking, employed a fabrication method that was much more human-friendly. This allowed for a much more 'interactive' design process with the human co-designer acting directly with the material system on the same terms as the robotic arm – through simple re-location of bricks. However, in this study the robotic stacking process followed a deterministic robot program generated with the computational design framework, thereby limiting the co-designing aspect to a process in which the robot places a fixed series of bricks and the human agent, based on emerging design intentions, makes ongoing alterations to the brick composition. In this scenario, the human co-designer can only alter the position of a brick after it has been placed and only to the extent that this repositioning doesn't interfere with the placement of the following brick – leading to a collision. This issue could be overcome if the human co-designer were allowed to intervene in the deterministic fabrication process and, through interaction with the robot, change the placement and orientation of each forthcoming brick, before the robot places it. This could lead to a fabrication process in which the robot continually moves to a pre-planned location of a new brick to communicate its 'intention', but then permits changes to that location based on human interaction, before finally placing the brick. This potential interaction between human and robot could support a robotic-based design/fabrication process where the robotic fabrication sequence/code could be left 'incomplete' with known uncertainties for instance regarding correct brick placement or lacking brick support, as this could instead be solved-on-site.

Similar to Design Study 1, which explored robotic concrete extrusion, this study entails a design process in which designing and exploring the design framework and exploring designs with the design framework progress simultaneously. The design system and the design solutions it enables mutually inform each other and continuously reshape the boundaries/restrictions of the problem-solution space, defining new relationships and establishing suitable problem-solution pairs – a process of 'co-evolution', as described by Maher (Maher, 1994). Another similarity between these two studies is the author taking on the role of both developer and user of the design system. Referring back to Boden's definition of the three forms of creativity, *combinational creativity*, *explorational creativity*, and *transformational creativity* (Boden, 2004), it can be argued that the ability to change and adapt the design tool (or in this case a design system) supports not only explorational creativity, in which novel ideas are created within the restrictions of a given conceptual space but also transformational creativity, in which a person realises the limits of a given conceptual space and decides to transform that space.

5.2 Design Study 4: Robotic Brick Stacking II

5.2.1 Introduction

As discussed in the previous study, several aspects of human-material-robot processes need further attention to extent investigation into design methods for interactive robotic-based design exploration. When seeking to establish design methods for supporting robotic-based design processes, it is essential to investigate how this fabrication-driven process, or mode of designing, ties into established modalities in the field of architectural design. As mentioned in chapter 3, the relevance and implications of modality shifts during design exploration are discussed by Julio Bermudez and Kevin King:

> *"Multiple iterations of analog-digital media interactions enhance the design process. The phenomena of transition (smooth or problematic) and re-interpretation required to move between media are of great importance as they enhance the design process in cognitive, qualitative, and productive terms." (Bermudez and King, 1998)*

Although their investigation was concerned with the advent of digital systems in architectural offices and academia in the late '90s, and the impacts this would have on current analogue design processes, a similar hypothesis can be made concerning the integration of robotic fabrication. Implementing a design framework that supports interactive human-robot processes and simultaneously allows for design exploration with analogue design methods (drawing and model making) could allow an investigation of the occurrence and effects of modality shifts during robotic-based design exploration.

Another crucial aspect is the integration of human-robot co-fabrication and the potential of leaving specific fabrication procedures undetermined or unsolved, to be addressed during fabrication by the interaction and assistance of a human co-worker. This aspect holds the potential of lowering the level for how well thought out, or how detailed, the fabrication sequence needs to be for a robotic fabrication process to commence. This approach could positively impact the time required to transition from representative design processes (both analogue and digital) to physical material-based fabrication processes. This faster transition could potentially lead to smoother and faster design iterations, thereby supporting increased creativity. Also underpinning a successful co-fabrication process is the applied robotic technology. Until now all design explorations have utilised an industrial robotic arm designed for fast and powerful movements, and although this has allowed for fabrication processes like robotic milling and precise moving of a heavy concrete extruder, it also demands high safety measures, thereby limiting the opportunity for "face-to-face" collaboration. Therefore, the following study instead makes use of a collaborative robotic arm that, although smaller and less powerful, enables safe and even direct hand-based movement of the robotic arm.

With a background in the findings of the previous study, and intending to extend the

Figure 5.6.
Interactive robotic setup with UR10 robot, plywood/foam bricks and the computational framework running on laptop in Rhino/Grasshopper.
Photo by Mads Brath Jensen.

proposed design framework to support interactive human-robot design processes, this study investigates the impact of human-robot co-fabrication based on the design process of non-expert design students. Through qualitative user observation, quantitative logging of modality shifts, and completed questionnaires, the study seeks to identify critical aspects for the successful integration of interactive human-robot design exploration – aiming to contribute to the advancement of new explorative design methods.

The study has been disseminated through the journal paper "A Framework for Interactive Human-Robot Design Exploration" (Appendix D), referred to as 'Paper 4'. The focus and scope of this journal paper allowed thorough dissemination of the applied methods, the associated results, conclusions, and relevant topics for discussion. Therefore, the following section seeks to elaborate on the collected findings of the studies presented in this section and relate them to the previous work in this thesis.

5.3 Collected Findings and Discussion

Resistance of material systems

The two studies presented in this chapter both explore design solutions for brick-based material system, one concerned with limestone and the other with a combination of plywood and foam, as shown in figure 5.6. Although each of the two design explorations depends on materials of a different category (stone and wood), featuring each their set of inherent properties, they both restrict the changeability and diversity of the material system into one fixed variant – a simple brick geometry. The reason for this simplification of the applied material systems is based on the desire to investigate aspects concerned with human-robot co-fabrication, which based on the results of Design Study 1, was to a large degree hindered by the time-restricted processes of material curing, or as in Design Study 2, by the security risks related to the subtractive fabrication process. Although simplifying the complexity of the material systems, in the two brick-based studies, has enabled co-fabrication processes in which both human and robot participates, it has also reduced the material systems to mere geometric systems. Changing the material of the bricks, to for instance plastic, cork, or aluminium, would not have changed the human-robot design exploration and fabrication, except for the acoustic simulations which due to the sound-absorbing and -reflecting properties of the material would have led to different sound performances. So, although simplification of the material system has allowed for a focus on, and advancement of, other key aspects, the brick-based studies has also indicated that a re-introduction of material diversity might generate the resistance needed to substantiate the continuous switching between computational design processes and human-robot exploration of physical material systems. If the resistance of the material system is low enough and all essential aspects of material behaviour and fabrication logics are anticipated, allowing for highly accurate computational simulations of design solutions, then the necessity for physical human-material-robot processes fades. This scenario was to some degree encountered in Design Study 4, where the registration of shifting design modalities showed peri-

Figure 5.7.
Student physically interacting with the robotic brick stacking process. The proposed computational design framework allows the user to activate the UR robot’s freedrive mode and physically move the robot arm to a desired location.
Photo by Mads Brath Jensen.

odic declines in the students' use of robotic fabrication. As mentioned in 'Paper 4', this temporary decline can be explained by the students obtaining sufficient understanding of both the dynamics of the material system and the procedures related to robotic fabrication – allowing them to sustain a highly iterative computational design process that closely approximated the restrictions of the physical environment.

> *"Increased applicability of interactive robotics can be achieved by exploring material systems with more complex inherent properties that are more difficult to predict and control during the fabrication process." (Appendix D)*

The need for human-material-robot design exploration is, as stated in 'Paper 4', presumably linked to the resistance of the material system - an aspect that needs considerations in future work.

Human-computer-robot communication

Human-robot communication was investigated, including both gesture-tracking, live numeric-based communication via teach pendant and Grasshopper, as well as physical hand guiding of the robot by using the UR's freedrive feature. These are all communication from human to robot, but the design system also sought to explore robotic-based gestures allowing the robotic arm to hint at its "intention", for instance when waiting for human interaction or when seeking to show where the next brick would be placed. Push-buttons on the fabrication table also allowed for quick and reliable acknowledgement of robot actions and ensured that human and robot were synchronised and on the 'same track'.

Further development of the computational design framework also allowed an exploration of direct communication between the robotic arm and the Grasshopper definition. Using a TCP-connection data regarding the current position of the robotic arm and the state of the robot, either 'busy' running a program or 'ready' to receive a new one, could be accessed at any time. Likewise, data containing robotic commands could also be streamed from the Grasshopper definition to the robot. This allowed for a fragmentation of the robotic program, where instead of transferring robotic instructions for the fabrication of a complete wall, the procedure is divided into individual 'per brick' instructions. This enables the designer to make changes to the design during fabrication and proceed with an altered fabrication scheme.

Allowing the designer to communicate with the robotic arm during fabrication, and more important to make changes to the fabrication process, gives rise to un-anticipated and cascading effects, potentially leading to novel ideas and new design insights, but may also lead to unbuildable structures. The interactive human-robot processes supported by the design system in study 4, made it possible for the designer to change the location and orientation of any brick during fabrication. During the parametric design process, each brick within a wall assembly is checked for collision with neighbouring bricks and flagged with an error if collision exists. Although this process ensures that the wall is buildable before proceeding to robotic fabrication, it does not anticipate any human-driven alteration of brick positions. Because the

Figure 5.8.
Physical demonstrator of the acoustic brick wall. Exhibited in the Utzon Center, Aalborg, Denmark
Photo by Mads Brath Jensen.

position of all bricks are determined before fabrication is initiated, the design system is not capable of adapting and repositioning the bricks based on this 'unexpected' human change. This means that if the designer changes the position of a brick during robotic fabrication, the robot unknowingly proceeds as planned and risk a collision when placing the next brick. The designer, if introducing any changes during fabrication, has to accommodate the adaptation of the following bricks to prevent brick collisions, or in some cases also lacking support of the next horizontal layer.

As mentioned in the Introduction chapter, methods and processes for robotic-based adaptation during fabrication have been investigated by Pigram, Maxwell and McGee, which led them to define the strategy Adaptive Part Variation (APV), where *"… the real-time redefinition and fabrication of parts occurs during the serial process of assembly thereby allowing detected errors to trigger a conditional design response.*" (Pigram, Maxwell and Mcgee, 2016). One of the essential requirements for this proposed workflow is the registration of variance during fabrication and the ability to update the digital model based on these registrations. In the project described by Pigram et al. inaccuracies, involved in the bending and welding of steel rods, required laser scanning for registration of variations in the position of the steel parts. The brick stacking process in Design Study 4, however, only relies on robotic positioning of bricks, with variations introduced by the human co-worker only taking place through interaction with the robotic arm, and thereby variations in brick positions can be registered by tracking the position of the robot during brick placement. Following the APV strategy, the aspect currently missing in the computational framework from Design Study 4 is the ability to trigger a conditional response. More specifically the capability to reconfigure and adapt the position of the remaining bricks, enabling the continued fabrication of a buildable wall. Although integration of a conditional response within the computational framework is feasible, it presents an added complexity to the parametric setup and demand that the designer, before fabrication commences, has considered how the system should respond to a given variation. Although engaging with this level of parametric logic presumably requires competencies that exceed those of the students involved in these studies, it would be a requirement for engaging in robotic-based exploration of more versatile and complex material systems.

Intention and decision-making

Although only briefly mentioned in the two papers associated with the studies presented in this chapter, the role of design intention and the allocation of decision-making are essential aspects to reflect upon when striving towards closer interaction, or even collaboration, between human designer and robotic fabricator. In 'Paper 4' it is made quite clear that: *"…for each of the three interaction modes the design intention and decision-making lie solely with the human designer – the robotic arm, and the interactive system driving it, only responds through pre-set interaction scenarios*" (Appendix D).

As the robots used throughout both brick stacking studies were not given the ability to sense their environment, they had no opportunity to react or adapt to changes during the co-fabrication process. Thereby, all intention and decision-making were located at the human designer, and, to reference Murphy's division (Murphy, 2019), the robot was merely treated as a tool (see discussion in chapter 3.3.). Although only utilising the robot as a tool, the co-creative robotic design system allowed for higher degrees of interaction, and consequently increased engagement, during the ongoing fabrication process. To obtain co-creativity, future investigations must ensure that decision-making is shared between human and robot. This requires that the robot can sense its environment and that the co-creative robotic design system can merge existing computational evaluation and simulation routines with a framework that allows the robot to generate goals and intents and to select and plan for how best to meet those goals and intentions.

References

Bermudez, J. and King, K. (1998) "Media interaction and design process: Establishing a knowledge base," in *Digital Design Studios: Do Computers Make a Difference? ACADIA Conference Proceedings*. Cincinnati, Ohio: Cumincad, pp. 6–25. Available at: https://cumincad.architexturez.net/doc/oai-cumincadworks-id-029f.

Boden, M. A. (2004) *The Creative Mind: Myths and Mechanisms*. 2nd editio. London: Routledge.

Foged, I. W. *et al.* (2016) *Bricks / Systems*. Edited by I. W. Foged. Aalborg University Press.

Maher, M. lou (1994) "Creative design using a genetic algorithm," in Khozeimeh, K. (ed.) *Computing in Civil Engineering*. Nwe York: American Society of Civil Engineers, pp. 2014–2021.

Murphy, R. R. (2019) *Introduction to AI Robotics*. 2nd edn. Cambridge, MA: MIT Press.

Pigram, D., Maxwell, I. and Mcgee, W. (2016) "Towards Real-Time Adaptive Fabrication-Aware Form Finding in Architecture," *Robotic Fabrication in Architecture, Art and Design 2016*, pp. 427–437. doi: 10.1007/978-3-319-26378-6.

6.

Co-creative Robotic Design Exploration

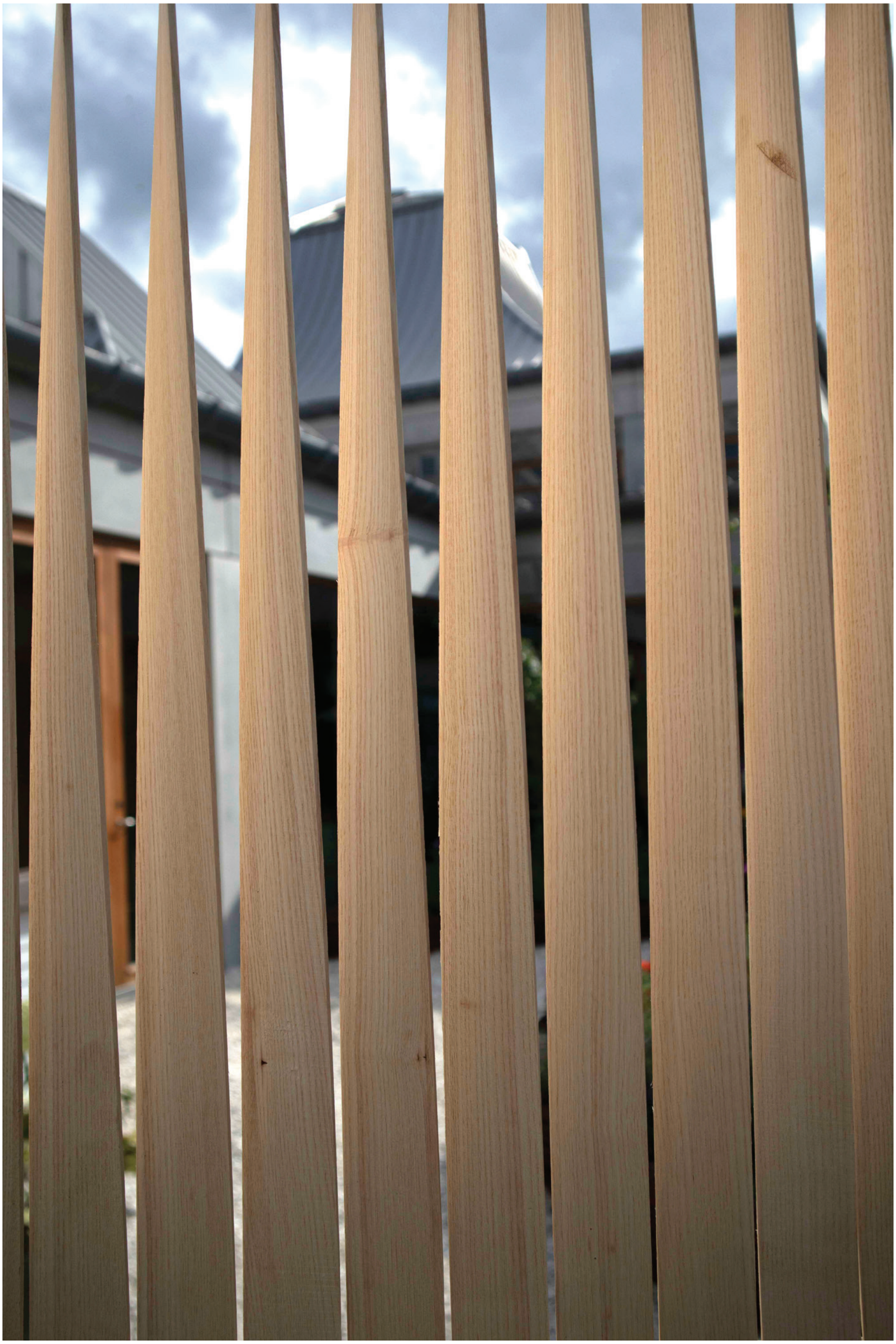


Figure 6.1.
Physical demonstrator of the wood lamella facade. Exhibited in the Utzon Center, Aalborg, Denmark.
Photo by Mads Brath Jensen.

6.1 Design Exploration 5: Robotic Wood Bending

6.1.1 Introduction

The findings in Design Study 4, as presented in the previous chapter, elaborated on the construction and user-driven evaluation of an interactive human-robot design method and the design processes it enabled. Through the development of a computational framework, the study allowed for human intervention during robot fabrication; thereby supporting indeterministic and explorative fabrication sequences. Yet, the study also identified particular situations within the design processes, where robotic reconfiguration or adaptation could be advantageous, or even necessary if the limitations and simplifications of the material system are to be overcome.

Concerning the brick stacking procedures in Design Study 3 and 4, it was suggested that the robotic fabrication framework could reconfigure the positions of consecutive bricks according to the deviations, as an effect of human intervention, of previous brick placement. Such adaptation procedures would be of a similar type as the ones previously described in the Adaptive Part Variation (APV) strategy by (Pigram, Maxwell and Mcgee, 2016) where detected errors trigger conditional design responses. Although such adaptive fabrication processes allow for an exploration of increasingly complex and dynamic material systems, it can be argued that these fabrication processes are mostly occupied with automated adaptation to fabrication-related errors. In such processes, the robotic arm is seen as a solitary, albeit intelligent, worker – what Murphy referred to as treating the robot as an agent, as discussed in chapter 3.3. The objective of the thesis is, however, to investigate co-creative robotic design systems. The project thereby aspires to the establishment of joint cognitive systems in which robots, as discussed by Murphy, are treated as parts of a human-machine team with both agents contributing to the collective intelligence of the team (Murphy, 2019).

To pursue the investigation of such co-creative design methods, this design study seeks to advance on two key points: implementation of sensing capabilities on the robotic arm to allow for registration of selected features in the material system, construction of a computational framework that can generate design variations and suggest design alterations based on the changing state of a physical material system.

The design study has been disseminated through the conference paper "Technologies and Techniques for Collaborative Robotics in Architecture" (Appendix E), referred to as 'Paper 5'. The publication aims to present the technological and methodological aspects related to the construction of an interactive robotic-based design method. By focusing on the integration of visual analysis features and the creation of a state machine for controlling the interactive human-robot workflow, the paper constitutes the technological foundation for establishing a co-creative design method and exploring the design processes it facilitates.

The following section will elaborate on the creative process afforded by the collaboration between a "*...holistic-driven human designer and a performance-driven solution-proposing robot"* (Appendix E). Design Study 5, containing the last experiments

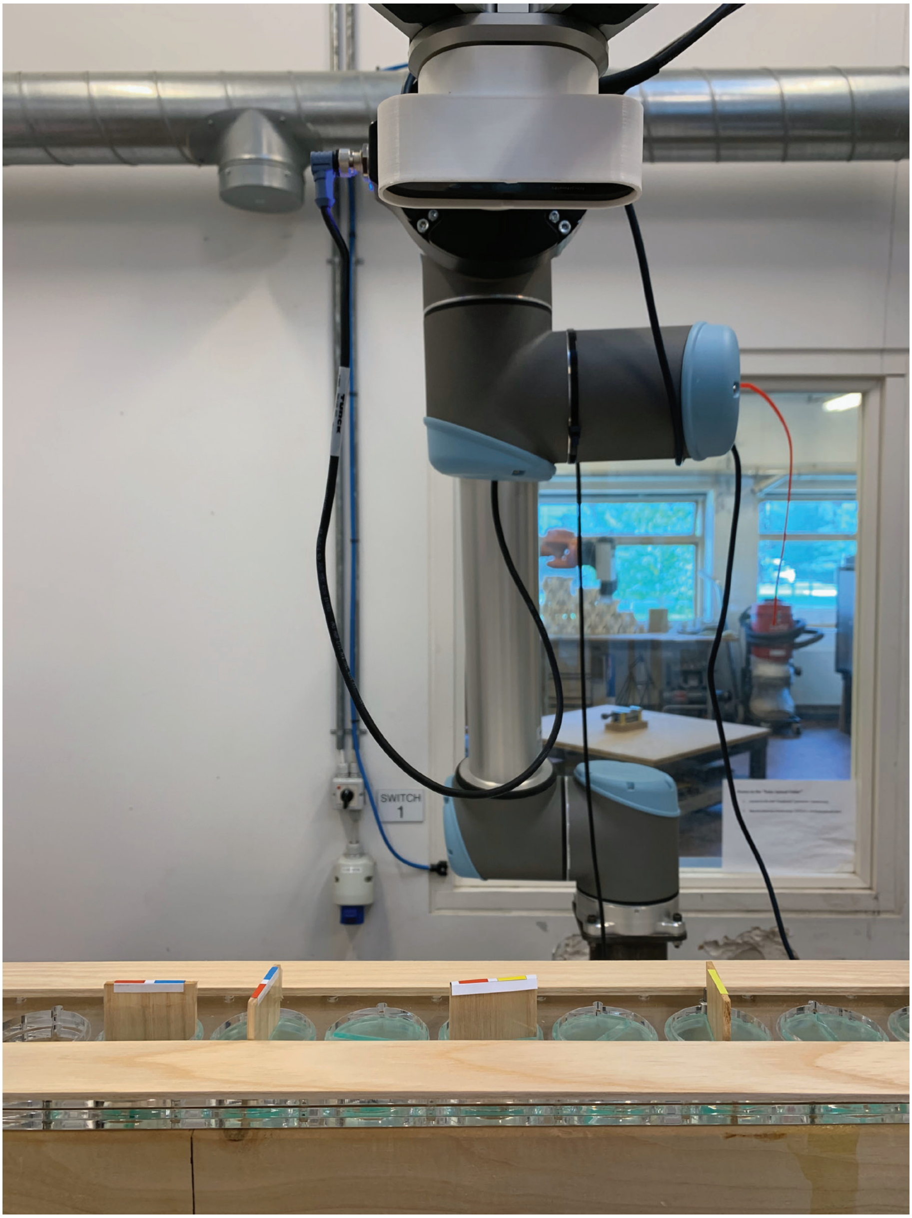


Figure 6.2.
Initial experiments with visual analysis. Variations of colorured markers placed on the top of the wood lamellas are registrated by a camera mounted on the robotic arm. Red and blue were found to the best regocnisable colours and allowed a computational analysis of the wood lamella's rotation angles. Photo by Mads Brath Jensen.

conducted during the thesis, did not arrive at its full conclusion within the period of the PhD. As a result, the following section will discuss the preliminary observations obtained during the study. The methods, result and preliminary conclusions associated with the design study is presented through 'Paper 5' in Appendix E.

6.1.2 Discussion

As mentioned above, this design study aimed to investigate co-creative design processes through the implementation of a sensing robot capable of recognising changes made to a material system and proposing new design solution. To explore such creative processes, the study constructed a bespoke façade system consisting of 24 rotatable wood lamellas and installed a robotic arm equipped with an electric gripper and a standard web-camera (a full description of the setup is presented in 'Paper 5'). The intention behind the human-material-robot setup was to establish a co-creative design process in which both the human designer and the robotic arm could interact and propose changes to the material system – supporting a joint exploration of the problem-solution space associated with the shading and view directing façade system. In this joint cognitive system, the human designer provides a design intelligence based on aesthetic, spatial, material, technical and social understanding (the list merely representing a short extract of course), while the intelligence provided by the robot is based upon analytical processes involving simulation of the shading and view-directing performance of the façade system. The robot co-designer thereby adds a performance-driven intelligence to the 'design team' that lies outside the reach of the human co-designer – offering the potential for creative and explorative dialogue.

Communicating design intentions

The co-creative system established during this study ensures that both the human and robot agent can propose changes to the material system. By unlocking the rotation mechanism, installed at the top of each lamella, every single wood element can be rotated within a -90 to 90-degree range. Rotation of each wood element can be carried out solely by the designer or, if the robot is suggesting changes, by a collaboration between human and robot, in which the robot performs the rotations and the designer opens and closes the locking mechanism. In situations where the robot suggests changes on the system, the intended actions are communicated through gestures performed by the robot. The anthropomorphic properties of the robotic arm allow for human-like gestures such as pointing towards an object, opening and closing of hands to communicate a 'ready for action' state or simulating a 'tilting of the head' movement to express increased interest. An interesting example of such animated robotic behaviour is presented in a collaborative human-robot drawing project by (Hinwood *et al.*, 2018), where the behaviour of a robotic arm affect the participants' drawing experience. In this study, the robot gestures its intentions through pointing motions and by making short rapid rotations of the wrist to signal an impatient 'waiting for action' behaviour.

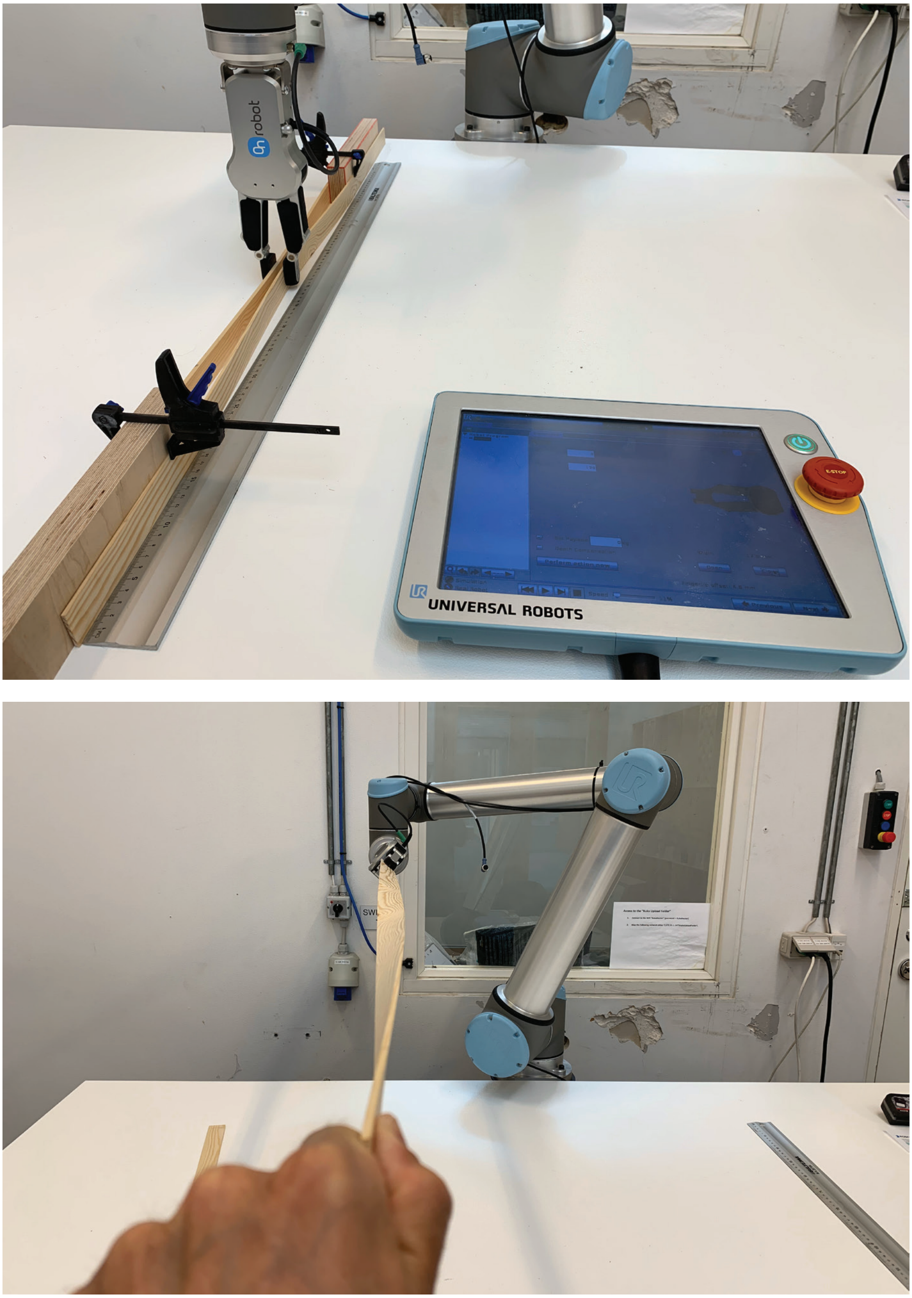


Figure 6.3.
The UR robot was used in the inital material explorations of wood lamellas. Varying thicknesses were tested to understand their capacity for bending along different axis. The force control in the electric gripper allowed for insights into the relation between material dimensions and acquired bending force. Photos by Mads Brath Jensen.

Although these robotic gestures allow communication of action-directed intentions, the robot does not support communication of more complex design intentions, like why a specific set of wood lamellas need to be rotated in a specific manner. The pattern of reasoning that drives the robot's proposed changes to the façade system is not directly accessible to the human designer. During the preliminary explorations of the co-creative design system, the issue with direct communication resulted in a lasting dependence on utilising the computational design framework as the main instrument for the communication of design intentions. The parametric interface of the computational framework allowed for both modification of the systems' variables and constraints as well as defining the performative search criteria that drives the robot's design intentions. When running the co-creative design process, the computational interface is used to visualise the iterative search through design variations allowing the human designer to see and understand the robot's 'cognitive process' – the thought pattern that supports its decisions. The initial experiments in this study show significant differences in participating in a co-creative robotic process with or without the opportunity to see the interface of the computational design framework. Without visual access to the simulated design model and the conducted performance search, the coordination and cooperation between human and robot are hindered, making it impossible to reach shared design intentions and goals. The preliminary findings of the design study thereby argue that the issue of communicating design intentions is crucial for the cognitive aspects related to co-creative robotic design processes in architecture.

Cognitive Load

Compared to the previous design studies presented in chapter 4 and 5, this study expands the computational framework of the design systems to allow for the generation of potential design variations, based on information of the current state of the physical material system. This advancement of the computational processes enables the robotic arm to sense (with camera and computer vision techniques) the state of the material system, iterate through design variations in search for better solutions, and pass on instructions to the robot for execution of these design changes.

From a user perspective, the extensions allowed for a simple co-creative design process where the designer can manipulate directly with the material system and implement a set of design changes. These design changes can then be registered by the robot, which suggests improvements to the material system by directly engaging in a user-assisted reconfiguration of the wood lamellas.

This development of the co-creative design system allowed a transfer of design conditions away from the human mind and into the computational model, thereby freeing up the cognitive load. Still, simultaneous more energy needed to be invested in managing the growing complexity of the computational model. The computational framework was extended to manage communication between several sub-systems and included state machines that, based on user input and sensor data, controlled the sequence and initialisation of several response scenarios. As argued in Design Study 5, this development calls for improved methods for handling the growing com-

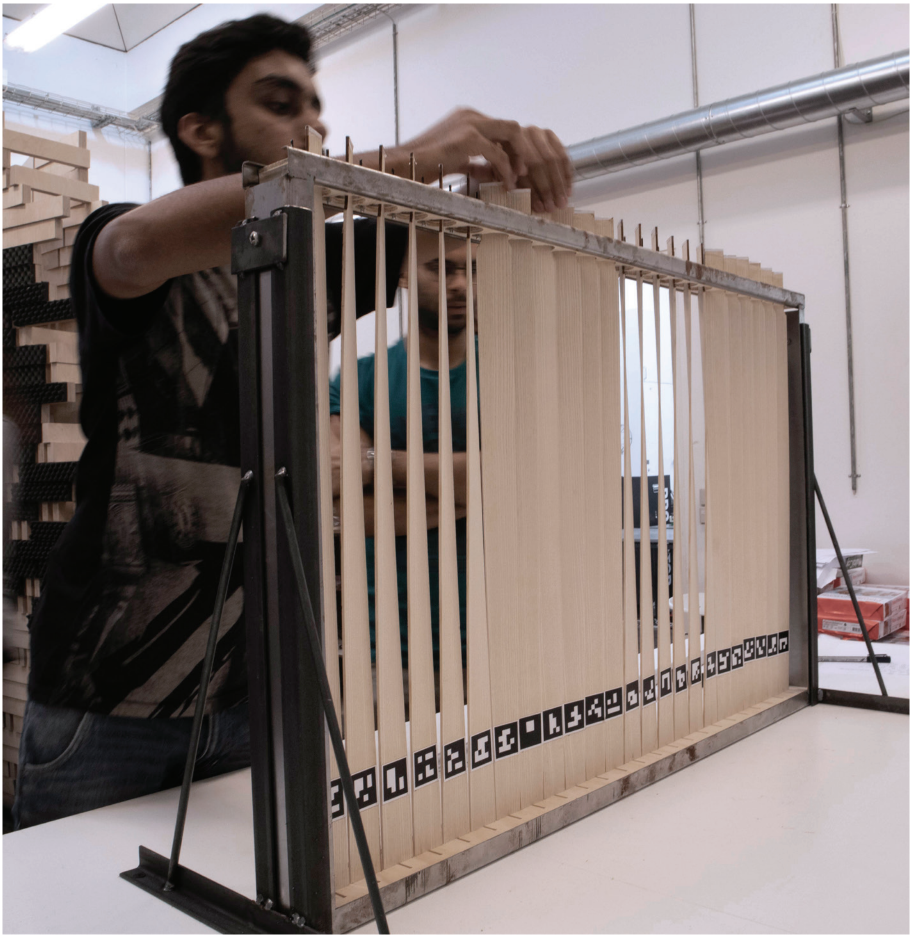


Figure 6.4.
Student interacting directly with the wood lamella facade element. By releasing the locking mechanisms in the top rail, the user can rotate each lamella to a desired position, allowing for easy investigation of new design variations. The black/white ArUco markers placed at the bottom of each lamella, in combination with the custom colour markers attached to the top of each lamella, allows the robotic arm to perform a visual analysis routine and update the digital model of the facade system. This enbales the computational framework to search for improvements to the facade system, to be executed through the actions of the robotic arm.
Photo by Avishek Das.

plexity of the computational framework. In this study, especially the management of the many sub-routines and the complexity involved in introducing changes within the sequence of logical states, lead to an increased cognitive load and impeded the creative process. In the same manner, as robotic simulation and control have been simplified and made accessible through software plugins like KUKA-prc, Robots (visose), and HAL, the handling of human-robot interaction scenarios could also be supported by developing the proposed state machine setup, together with other computational methods deployed during this thesis, into user-friendly software components. During the study, such an approach led to the development of three simple Grasshopper components, in combination facilitating the configuration of the visual analysis routines.

Creative Flow

As mentioned above, regarding the communication of design intentions, initial design explorations with the co-creative robotic design process were conducted with and without the opportunity to see the interface of the computational design framework. As this visual interface is currently the only method for understanding the decision-making processes and the design intentions of the robotic system, not having access to it hinders collaboration significantly. However, there's another essential aspect that is negatively impacted when robotic decision processes are obscured from the designer, the feeling of being in a creative flow.

According to Nakamura and Csikszentmihalyi's definition of flow, as described in chapter 3.1.2, one of the essential conditions are the existence of: "*clear proximal goals and immediate feedback about the progress that is being made*" (Nakamura and Csikszentmihalyi, 2005). From the previous discussion of shared human-robot design intention, and the lack thereof, it is evident that the existence of clear goals is an issue that currently affects the experience of creative flow. Concerning the importance of immediate feedback, the co-creative design system is, as mentioned above, challenged by the lacking feedback regarding robotic decision-making processes. Although not the most integrated solution, access to the visual interface of the computational framework does, however, pose as a solution for managing the shared human-robot design goals and for supplying relevant feedback during the design process. Concerning Nakamura and Csikszentmihalyi's condition, the challenge of maintaining creative flow thereby comes down to the word 'immediate', which specifies the importance of time, when seeking to maintain flow.

The expansion of the computational design framework, including the computation of sensor data, the performance-driven search for more suitable design variations, and the calculation of robotic response scenarios, requires extended computing time. Due to this extension of the robot's 'thought process', initial design experiments with the co-creative design system revealed that the designer has to passively wait for 30-120 seconds (depending on the chosen search criteria) while the robot 'contemplates', reducing the feeling of being in a creative flow. How this waiting time is experienced does, however, depend on the visual access to the robot's decision-making process – observing the computational search process allows the designer to gain insights about the selection process and the feeling of immediate feedback is present.

Figure 6.5.
Close-up of the wood lamella facade elements.
Photo by Avishek Das.

Based on these findings related to the creative flow, it is argued that the time spent on robotic decision-making processes is a crucial aspect in obtaining a successful co-creative design process. But, as the processing time cannot be avoided entirely, it is essential to take advantage of these periods and ensure that relevant knowledge is shared and communicated within the human-robot design team. How to communicate within the human-robot team, by a computer screen, video/image projections, custom displays, augmented reality headsets, or a mix of these technologies is an interesting aspect for future research.

Robotic Intelligence

The co-creative robotic design system established in this study has allowed a human designer to collaborate with a sensing and acting robotic arm. The robot can sense the changes that the designer makes on the material system. It can use these registrations to update the digital model of the material system. Based on the updated digital model, the computational framework enables a performance-based search for new and more suitable (based on the selected design criteria) design variations. When a better performing design solution has been found the robot, with assistance from the designer, can act on the system by rotating selected wood lamellas. The designer can now reflect on the robot's design suggestion and respond by making new suggestions, and so the loop repeats.

There is, however, one limitation to this co-creative and iterative design process; it is only the designer that learns from it. The robot has no memory. Each time the process iterates, the robot resets and restarts its decision-making process and information regarding the previously calculated design solutions are deleted. This has the unfortunate result that the robot might re-introduce already examined and discarded solution leading to a design process in which the designer improves on the result along a given intention-driven trajectory. In contrast, the robot merely suggests random improvements. This co-creative challenge suggests for further research into robotic intelligence and the expanding field of artificial intelligence, intending to uncover suitable methods for machine learning.

References

Hinwood, D. *et al.* (2018) "A Proposed Wizard of OZ Architecture for a Human-Robot Collaborative Drawing Task," in Ge, S. S. et al. (eds) *International Conference on Social Robotics (ICSR 2018)*. Cham: Springer International Publishing (Lecture Notes in Computer Science), pp. 35–44. doi: 10.1007/978-3-030-05204-1_4.

Murphy, R. R. (2019) *Introduction to AI Robotics*. 2nd edn. Cambridge, MA: MIT Press.

Nakamura, J. and Csikszentmihalyi, M. (2005) "The Concept of Flow," in Snyder, C. R. and Lopez, S. J. (eds) *Handbook of Positive Psychology*. 2nd edn. New York: Oxford University Press, pp. 89–105.

Pigram, D., Maxwell, I. and Mcgee, W. (2016) "Towards Real-Time Adaptive Fabrication-Aware Form Finding in Architecture," *Robotic Fabrication in Architecture, Art and Design 2016*, pp. 427–437. doi: 10.1007/978-3-319-26378-6.

7.

Conclusions

This chapter presents the overall conclusion of the thesis. First, to recapture the point of origin, a look back to the initial problems and research objectives is provided. This section is followed by a summary of the first six chapters, leading to a sequential reiteration of the research questions and their potential answers. Finally, a reflection on the research findings and suggestions for future work concludes the thesis.

7.1 A short recap

The initial inquiry of the thesis originates from personal experiences with digital fabrication processes, obtained through almost a decade of scientific research and university teaching within the architectural domain. In reflecting on several critical explorations of computational design methods, all aiming to challenge the potential integration of digital fabrication technologies, a lack of interaction and collaboration between designers and the ongoing fabrication processes was recognised. This lack of active engagement within the act of making constituted the initial problem.

Inspired by the affordance and accessibility of robotic arms, the thesis showcased several innovative projects derived from the growing field of robotic fabrication. It framed an argument towards the potential implementation and utilisation of interactive and collaborative human-robot design processes. To appreciate the influence that robot-based design methods might have on cognitive design creation, suitable theoretical sources from cognitive science was presented. The framing of the prospective fields of interest led to the establishment of a research objective that seeks to study how architectural design 'solutions' and design 'problems' can be investigated through interactive and collaborative robotic fabrication frameworks. On an applied level, the thesis seeks to formulate, construct and showcase design methods and computational design workflows for establishing a direct relationship between the intuitive design processes of the designer and the analytical robotic based evaluation and actuation properties.

Chapter 2 presents the research design and, with reference to Ian Hacking, argues for the creation and critical observation of phenomena as the potential pivot of the research strategy. In line with this strategy, the thesis further advocates for design research performed through experimental work, adhering to the research-through-design methodology. To elaborate on the chosen research method, the chapter further discusses the critical role of the experiment and how this relates to the research motivation, hypothesis, research questions, evaluation and knowledge production.

Chapter 3 outlines the scope of the multidimensional field encompassed by the proposed human-robot design framework. To support the objective of merging these domains into a seamless methodological framework, relevant theoretical and methodological aspects of each domain is accumulated. The chapter begins with a discussion of design thinking and looks at existing design methods and their theoretical underpinnings, thereby revealing inherent design activities and their potential for incorporating robotic-based design processes. The chapter defines what creativity is and how theories related to creative thinking might be included in human-robot design processes. The chapter concludes with a discussion of creative flow and the importance of considering design experience.

Chapter 4 elaborates on the findings of the first two research experiments, both associated with the category of 'informed robotic design exploration'. The first experiment deals with the development of a design framework that enables and facilitates robot-based design exploration. By constructing a robotic system for concrete printing, the experiment examines a design framework and showcases the potentials and challenges of utilising such frameworks. Based on these findings, the second experiment seeks to address the concerns related to the internal complexity of the investigated material system and the growing technical requirements and their impact on the creative design process. Through the setup of a design studio, the experiment implements and applies a robot-based design framework and evaluates its impact on the creative and cognitive processes of non-expert designers.

Chapter 5 presents two experiments that both investigate the category of 'interactive robotic design exploration'. Advancing from the knowledge acquired from the two first experiments, these experiments both investigate and incorporate a material system composed of bricks and explore different human-robot interaction methods. The first of the two experiments deal with the construction of a computational framework that allows for the integration of human-robot co-fabrication and the potential of leaving specific fabrication procedures undetermined or unsolved. The second experiment extends the computational framework and introduces selectable modes for human-robot interaction. Through qualitative user observations of architecture students, the experiment studies how designers interact with robotic arms and evaluates the possible impacts on creativity and the utilisation of selected design modalities.

Chapter 6 presents the final experiment. The experiment establishes a collaborative and co-creative human-robot design method by integrating visual analysis features and a state machine for controlling the interactive human-robot workflow. By creating this design method, the experiment investigates the resulting design processes and their impact on human creativity.

7.2 Research Questions and Answers

Based on the research findings, the research questions formulated in the Introduction (chapter 1) can now be listed and addressed.

> *Q1. How can interactive and collaborative robotic fabrication contribute to the creative 'co-evolutionary' design process?*

Based on the observations in Design Study 4, it is shown that the opportunity for physical interaction with the robotic fabrication process increases design insights and support exploration of the relations between the material system and robotic fabrication. It is also evident that initial challenges regarding potential collisions in the robotic brick placement procedure can be overcome through the option of interactive repositioning of bricks. The possibility of hand-guiding or numerically informing the robotic arm during fabrication supports a trial-and-error-based approach in which an open-ended design exploration allows for indeterministic processes of robotic fabrication. The potential of deliberately including 'incomplete' robotic fabrication sequences is further discussed in Design Study 3. It is argued that a solve-on-site strategy for human-robot co-creation potentially creates opportunities for the designer to act on creative impulses. The robotic fabrication thereby shifts from an inflexible deterministic process to an adaptable approach to creative design inquiries. Based on the studies conducted in Design Study 4, it is further argued that the co-creative robotic design process allows for reflection-in-action, as defined by (Schön 1983) and promotes co-evolutionary processes that support the simultaneous act of thinking and doing. The findings suggest that the co-creative robotic design approach supports articulation of explorative 'what-if' questions, fundamental to the creative and iterative design process.

Also, from Design Study 1, 3 and 5, it can be argued that co-creative robotic design processes encourage co-evolution of design problem and solutions. Through increasing levels of human-robot collaboration, the findings from these studies all display design processes in which exploring the design framework and exploring designs with the design framework progress simultaneously. The robot-based design system and the design solutions it generates and fabricates mutually inform each other and continuously reshape the boundaries/restrictions of the problem-solution space, defining new relationships and establishing suitable problem-solution pairs through a process of 'co-evolution'.

In Design Study 4, similar co-creative design exploration is observed. During the span of the three-week design studio, the study also identified periods of declining utilisation of robotic fabrication. The study argues that the necessity for physical human-material-robot processes fades due to the "*acquisition and accumulation of specific design knowledge and understanding of the design variables at play*" (Appendix D). It can be further argued that for co-creative robotic design processes to contribute to design exploration, the properties of the material system and the intricacy of deployable robotic actions must form a collective problem space that resists immediate comprehension and control.

Based on observations of students' design processes conducted in both Design Study 2 and 4, issues associated with the proposed design system's computational complexity were identified as a barrier towards the creative exploration and reconfiguration of the problem-solution space. Although the two studies showcased student design projects with good integration of multiple design criteria, it was noticed that the design method restricted their exploration of non-standard formations and composition. This issue was especially evident in Design Study 4, where investigations performed through manual stacking of physical bricks displayed a much more comprehensive range of solutions than those explored through parametric modelling. In Design Study 4, it is argued that this negative impact is likely caused by a lack of computational software skills and insufficient experience in computational design thinking.

Reflecting on the overall findings of Design Study 2 and 4, it seems appropriate to suggest an extension to Research Question 1. Instead of opening the sentence with the words "How can…" it would be better suited to start with "How and when can…". The observations and questionnaires of these two design studies, supported by the subjective experience gained from developing the robot-based design methods, suggests that the robot-based approach "had a positive effect on the explorative design process, especially during the first days of design exploration" (Appendix D).

Q2. How are creative cognitive design processes influenced by interactive and collaborative real-time human-material-robot processes in architecture?

As argued in Design Study 1, which investigated robotic concrete printing, the iterative process of acquiring knowledge through robotic fabrication and computational design explorations and translating this into parametric design parameters/restrictions profoundly impact the creative and cognitive design processes. The study suggests that the continuous 'recording' of design restrictions and intentions stored through parametric relations in the design system can help free up the cognitive load of the architect. However, navigating the increasingly complex parametric network can also pose a mental strain that inhibits creative flow. The findings in Design Study 5 substantiates this conflict in which the computational framework shifts between freeing up and adding stress to the creative processes. In this study, the computational framework was extended to manage communication between several sub-systems. Based on user input, the integrated state machines controlled the sequence and initialisation of several response scenarios. The added computational complexity allowed a transfer of design conditions away from the human mind and into the computational model, thereby freeing up the cognitive load. However, with the opposite effect, managing the growing complexity of the computational model requires more mental energy. As argued in Design Study 5, this development calls for improved methods for handling the increasing complexity of the computational framework and for an extended computational skillset, achieved by advancing the designer's capabilities or by establishing interdisciplinary groups bridging towards disciplines such as robotics and computer science.

Design Study 5 also argues for the relevance of the sense of time in regards to creative cognition. The co-creative design processes established in this study require extended time for computing sensor data and calculating new robotic response scenarios. Initial design experiments with the co-creative design system revealed extended computing times, leaving the designer passively waiting and reducing the feeling of being in a creative flow.

The findings in Design Study 5 also points towards the issue of design feedback. The study pointed out that contrary to co-creative processes between two humans, the one between human and robot lacked sufficient strategies for conveying information. The lack of feedback resulted in difficulties in understanding the intentions of robot actions. A Challenge evident in Design Study 5, where the design system allowed the robot to suggest and perform changes to the material system based on environmental simulations that were not directly accessible to the designer. The robot could, in other words, perform a change to the design solution but not inform the designer about the underlying reasoning. The co-creative design system developed in Design Study 5 implements a comparatively simple method for robotic reasoning. However, it can be argued that issues related to the communication of design intentions are crucial for the cognitive aspect related to human-material-robot processes in architecture.

Q3. What impact does the integration of interactive and collaborative robotic fabrication have on the existing methods and processes supporting creative design exploration?

Design Study 3 shows that interactive robotic fabrication impacts the communication of fabrication data. In the study, the common file-to-factory approach is substituted by a 'fabrication generator', which, supplied with information regarding the specific robotic fabrication setup, generates a customised robot program that informs a robotic arm how to fabricate a prescribed brick wall in collaboration with a human co-worker.

Based on the studies conducted in Design Study 4, it can be argued that the integration of interactive robotic fabrication processes does not substitute traditional design modalities. From observations and logging of activity data regarding shifting design modes, the study suggests that "*varying aspects of the robotic-driven design process were explored by applying the work mode that best suited the task at hand*" (Appendix D). The study also indicates that how co-creative robotic design processes are integrated with existing design methods strongly relies on the designer's experience and familiarity with computational design and robotic fabrication. Difficulty in overcoming or dealing with design challenges through robotic fabrication processes was observed to shift towards other design modes. The study thereby indicates that robotic fabrication is applicable for exploring solutions in the early stages of design and supporting integration with existing design modalities.

Q4. What skills and knowledge-sets are required of designers to adopt and implement these technological advancements and their accompanying design processes?

Based on observations, Design Study 4 argues that computational design skills, including an appreciation of parametric software, is crucial to take full advantage of human-robot design processes. It is difficult, if not impossible, to specify a specific set of skills and knowledge required for successfully implementing and utilising human-robot design methods, as this is highly dependent on the trajectory of the design exploration. Based on the results of the computational design exploration of brick formations, shown in Design Study 4, it is demonstrated how the lack of computational skills limits the exploration of design solutions, as compared to the design solutions obtained through manual (physical) brick stacking, which displayed higher ranges of diversity.

Based on the studies conducted in Design Study 4, it can also be argued that the specific experimental setup utilised in the study allowed student participants to explore robotic fabrication, but that the same robotic setup simultaneously confined the students to examine only a given set of logical design procedures. In other words, the study supplied students with a robotic setup that allowed them to explore new design solutions, but due to their computational skill set, not a setup that they could radically change or divert from. This observation led the study to advocate for "*computational designers with the skills to explore the material system and overcome the restrictions of the computational/robotic system. In the same manner as Frei Otto constructed physical machines/devices for exploration of material design systems, designers in the field of computational-robotic design need the capability to build their machines/devices for design exploration*" (Appendix 4).

Q5. What are the requirements for a robot-based design framework that support interactive and collaborative design processes, and how might this design framework be constructed?

The studies conducted in Design Study 3 argues that adopting brick stacking as a robotic fabrication method, instead of the fabrication methods used in the previous studies (concrete printing and wood milling), affords increased opportunities for human interaction. As the study shows, the scale and material processes involved in brick stacking allow the human co-designer to act directly with the material system, as was not the case in Design Study 1 and 2. Due to the properties and processes afforded by the brick material, the designer can interact with the material system on the same terms as the robotic arm, although equipped with each their set of inherent abilities. The study thereby advocates for the exploration of material methods that, to a large degree, accommodate human interaction and the possibility for human-robot collaboration. Although direct human interaction with the material system is essential to ensure, discussions in Design Study 3 and 4 also stress that over-simplifying the brick-based system resulted in a geometric system that lacked material resistance.

The importance of the applied material system is further supported by the experiences gained from Design Study 1, where human interaction to a large degree was hindered by the time-restricted processes of material curing and from Design Study 2, where the security risks related to the subtractive milling process constituted the main hindering.

Based on the studies conducted in Design Study 3, it was suggested that allowing the designer to make changes during the ongoing robotic fabrication might lead to unexpected results and new design insights. This option was made possible and examined in Design Study 4, where the results showed that the introduction of unforeseeable human interaction required that the computational design framework was capable of adapting and responding to conditional changes. As shown in Design Study 5, the integration of conditional response methods requires that the robotic system is capable of repeatedly sensing its environment. The study showcased co-creation methods for a sensing and acting robotic design framework by implementing camera technology and visual analysis procedures. This study found that to support adaptive robotic co-creation, the computational framework has to implement methods for creating and managing robotic responses.

> *Q6. How can design variations, proposals, and intentions, generated by either the designer or the computational design algorithm, be communicated between the two entities?*

Design Study 3 showcases methods for implementing simple robotic gestures designed to prevent uncertainties during robotic brick stacking and inform a human co-worker about the robot's intentions. The study explored gesture-based interaction for simple communication with the robot, in this case, conveying the choice of brick selection and brick rotation through finger-counting methods. However, due to the lack of feedback concerning the correct reception of hand gesture by the system, gesturing routines were abandoned during the final fabrication process.

The interaction methods implemented in Design Study 4 facilitated simple robotic gestures, such as small alternating rotations of the robot's wrist, which successfully communicated robot intentions. This study also explored the freedrive mode of the UR10 robot, allowing the designer to move the robot to the desired position physically. Although the freedrive mode allows direct interaction with the robot, it did not allow the same positional accuracy that the robot arm otherwise afford. In Design Study 4, the issue of human-robot synchronisation was identified and investigated. The issue became apparent when fabrication tasks were divided between human and robot, and a need for communicating successful completion of a task had to be transmitted. Simple push buttons mounted on the fabrication table allowed for both quick and reliable acknowledgement.

In Design Study 5, design proposals from the robot were communicated to the designer through indicative movements and placements of the robot arm. In these scenarios, the robot would propose a reorientation of a specific wood element in the material system, move towards this element, and, through a 'pointing' position of the gripper (end effector), communicate its intention. In the specific study, suggestions given by the robot could be dismissed through push-button communication.

The experiments conducted in Design Study 5 also identified the challenges of recognising robot intentions and reading robot minds. The initial experiments in this study show significant differences in participating in a co-creative robotic process with or without the opportunity to see the computational interface of the design framework. Without visual access to the simulated model and the performance search that drives the generation of new design variations, the robot-based design process fails to support collaborative and co-creative design exploration, in which both human and robot intentions are shared and to some degree aligned. Without visual screen-based communication of design intentions, the human-robot design process risks turning into a design battle.

7.3 Conclusions

This thesis has intended to offer an alternative approach to robotic fabrication where the fabrication process is treated as an integrated element of a co-creative human-robot design process. This design approach appreciates human-robot interaction and collaboration as an essential aspect of design exploration. The thesis hypothesises that such co-creative processes of human-material-robot making can support and enhance the creative exploration of design modelling and design making in architecture. To identify potential challenges related to co-creative robotic design exploration, the thesis deploys a series of design studies, each aiming to design, construct, test and evaluate new design methods.

Based on the findings presented above, the proposed design methods progressively enhance interaction with the robotic fabrication process. The opportunity to directly interact with the robotic arm and suggest changes during the ongoing fabrication process allowed for the initiation of fabrication processes that were not entirely determined, thereby substantiating trial-and-error based design explorations that will enable reflection-in-action.

Based on the evaluation of the collected design studies, it is apparent that the benefit of robotic interaction within the design exploration relies heavily on the type of material system and the robotic fabrication method. If material systems are too simple or too intelligible, a limited experience can be gained from physical fabrication processes, and computational representations or simulation is more rewarding. This challenge was identified in Design Study 4. Through the overall progression of the design studies, a gradual decrease in the complexity of the material system can be registered, mainly due to the technological challenges in constructing the co-creative design methods. Decreasing material complexity must be recognised as a critical aspect of the applicability of co-creative robotic design processes. Regarding the robotic fabrication method, it has shown to be essential that the process is human-friendly. The designer can either engage with precisely the same fabrication processes as the robot (as seen in the brick stacking and lamella twisting) or with fabrication sub-processes deliberately kept human-only.

An important aspect in both the development and the application of co-creative robotic design methods is the technological challenge. Based on observation of the novice user groups, it was evident that knowledge of computational design thinking and experience with modelling software was decisive for overcoming the cognitive challenges imposed on the users during an application of the method. However, the design and interface of the computational framework did allow novice designers to engage with the interactive robotic fabrication without having to understand all the underlying computational processes. Still, changing the design restrictions imposed by the computational framework did act as a barrier to novice designers and hampered their creative processes. In developing the actual co-creative robotic design methods, the ongoing need for technological development also restricted the research activities. In developing robotic design frameworks, technical challenges appear in robotic control, in the engineering of end effectors, in the programming of sensors, in the management of data flow, and in the parametric setup of the design system – all challenges requiring knowledge of disciplines that have traditionally not been exposed to architecture. These diverse challenges call for an interdisciplinary approach to robotic architecture and the advancement of co-creative design methods.

The research and design activities accumulated throughout the thesis reveal that the investigation of co-creative robotic design processes requires a combination of research strategies. To observe and understand the creative impact of applying the specific design methods, the design process (the phenomena) must be established. Generating the requested design process requires the establishment of a novel design method for co-creative robotic design exploration. The research strategy thereby iterates between designing the co-creative approach, designing with this method, and observing the impact of the design processes it affords.

The last conclusion, and a trajectory for further research into co-creative robotic design exploration, is that if decision-making is to be shared between all agents in a co-creative human-robot design framework, the robotic framework must incorporate strategies for learning. In other words, there's a need for engaging with artificial intelligence and intelligent robotics to ensure that knowledge created during the explorative design processes is captured by all agents in the joint cognitive system, not just by the human designer.

7.4 Reflections

7.4.1 Research Investigations

Research Design

The arguments and proposals presented in this thesis are based on results obtained through a research strategy in which the creation and evaluation of experiments are seen as the primary vehicle for knowledge production. In pursuing such a research-through-design strategy, the author, in the role of the investigator, has taken direct action and sought to establish a co-creative design method that would allow an examination of its impact on creative design processes. During these investigations, the author has deliberately been placed within the experiments and simultaneously created and evaluated both the established design methods and the creative processes they afforded. The research strategy and the implied exploratory process has allowed a continuous reframing of research activities based on conducted experiments. Furthermore, the process enabled an iterative co-evolution of problem and solution space, as presented in chapter 2., and constant development of digital and physical design speculations, proposals and demonstrators.

The experiment-based approach might question the objectivity of the conducted research, especially concerning the evaluation of the creative impact related to the proposed design methods, as this relies on perceived experiences. To substantiate the findings relating to implementing the proposed design methods, the thesis organised two design studios with student participants. This approach allowed an accumulation of user observations, constructing a more objective position, and quantitative data regarding the conducted design processes and the corresponding impact on creativity. This mix of subjective and objective research methods has allowed for a more nuanced evaluation of the research findings. Although the thesis applied methods for collecting quantitative data related to the design processes of individual students, it is essential to recognise that this strategy was implemented to identify potential data patterns that might lead to new inquiries and not to validate the design method based on specific values.

As discussed in ‘Paper 4’ (Appendix D), the proposed design methods are only tested on students, categorised as novice users. Through this specific design study, it is further argued that computational design skills are vital for users to utilise the potentials of the proposed method in the best possible way. For that reason, it could have been valuable to examine the co-creative design method when used by expert designers with considerable experience in computational design.

Throughout the design studies, physical demonstrators have been applied to test robotic fabrication processes and the constructability of design solution generated with the co-creative robotic design methods. The realisation of the physical demonstrators did uncover unforeseen complications, especially regarding the human assembly of robotic-fabricated elements, leading to an enhanced understanding of the complex relations necessary for successful human-robot-interaction processes in creative design exploration. Although the physical demonstrators have been argued to constitute an essential method for representing and communicating research inquiry, little data was collected from the finished assemblies. Compared to the time invested in their realisation, which, especially in the first study with concrete printing, was considerable, more knowledge should have been extracted from this specific phase of the project.

Research in a cross-disciplinary field

The thesis has proposed new methods for creative human-robot collaboration and what can potentially be gained from such processes seen from a creative standpoint. Still, it has also shown how the implementation of such strategies requires an extended skillset of potential users. Although the notion of "human-robot co-creation" might suggest a focus on scientific developments concerned with communication and collaboration with robots, knowledge from several disciplines are needed to conduct proper research in this field. Broadly, investigations conducted throughout this thesis has employed knowledge from areas concerned with, for example, the properties and performance of material systems, collection and implementation of sensor data, mechanical construction of end-effectors, programming of custom software components, computational simulation of building performance, and control of interaction flows through state machines. These aspects are additional layers on top of the primary fields of architecture, design, and engineering. Their topics represent some of the disciplines and associated technologies needed to investigate robots and their potential impact on creativity. Such increase in technology and domain knowledge also demonstrates that the designer's activities get more complicated and not easier, as is typically expected when introducing and employing new technologies.

The robot-based design methods developed and investigated in this thesis were based on existing methodological and technological developments, including communication with robots through newly developed software add-ons, existing methods for simulation of daylight, and available industrial end-effectors for grabbing and moving materials. However, to answer the proposed research questions, developing essential technologies or constructing necessary computational methods were often needed. In addition, as the chosen research approach relies on both the development and application of human-robot design methods, the obtainment of valid research results greatly depends on the successful operation of highly technical research setups. Consequently, the design of research experiments has to some degree been restrained by access to existing technology and the authors' capacity (skills, knowledge, time) to advance the technological developments that can drive knowledge production. In combination with the desire to merge several distinct disciplines into one collaborative human-robot design framework, the need for technological developments prompt the question of if, and when, the design system becomes too complex? A question that should not only be addressed to the undertaking of research within this field but also towards the potential adoption of such design methods by the architectural practice. As the proposed design methods for human-robot co-creation are founded on a desire to promote creative design exploration, it is vital that the design framework allows for both stochastic design processes and shifting design intentions. This approach will require the establishment of an open-ended, adaptable, and highly customisable design framework. At the same time, a certain availability of pre-made options and automation features is needed to maintain a suitable level of complexity and ensure that creative flow isn't lost in the process of setting up and managing the human-robot design processes. Future developments for strengthening the applicability of human-robot collaboration in creative design exploration will be discussed in the final sub-chapter.

7.4.2 Human-Robot Co-creation

As presented in the Introduction chapter, the motivation behind this PhD study originates from the author's observations of the human designer acting as a passive observer during digital fabrication processes. The lack of human intervention and the consequent dependence on predetermined fabrication routines, planned and anticipated down to the last detail, gives rise to questions concerning the creative potentials of robotic fabrication. Can these robotic processes integrate and adapt to human interaction, and how can such human-robot processes affect the creative design process?

Based on the completion of five research studies and the increasing levels of human integration they afford, the thesis explores how humans can engage and become an essential part of a robot-based design system. The studies indicate that the development of dedicated design methods can facilitate a mutually supportive process in which human and robot contribute with each their skillset. In combination with their general adaptability and dexterity, the material sensitivity and spatial understanding of humans can serve as an extension to the precision, speed, and strength of the robotic system. Through the strategic use of applied research experiments, increased integration of human interaction within the robotic fabrication system was pursued and achieved. In retrospect, these explorative processes have identified varying levels of human-system integration, indicating potential benefits and challenges.

One aspect is the master-slave relationship between human and robot. This relationship is commonly used in traditional robotic fabrication processes, as utilised in Design Study 1 and 2. Humans thereby control and decide all actions needed to complete a fabrication task. In the robotic brick stacking experiment presented in Design Study 3, this human-robot relationship shifts towards a more collaborative robot-assisted fabrication process. With the human present and active in both the fabrication-informed design phase (acting as the master designer) and the fabrication process (acting as the robot-guided co-worker), the relationship shifts between master-slave and slave-slave, respectively. The slave-slave relationship, defined by the robot placing bricks and the human dispensing glue, both processes predetermined by the human designer, was, however, extended by the interaction procedures established in Design Study 4. Still exploring robotic brick stacking, this experiment allowed humans to interact during the ongoing fabrication process. By informing the robot (numerically or physically), human participants could alter the placement of specific bricks, thereby extending the creative process into the robotic fabrication process and allowing immediate response to changing design intentions. In this interactive brick stacking process, the human-robot relationship returned to one of master and slave; however, the experiment showed that this relationship could support co-fabrication processes, with both human and robot contributing with each their skillset. In seeking human-robot relationships that are more equally balanced and supportive of both the sharing of fabrication tasks and decision-making, the last design experiment (Design Study 5) investigated a collaborative co-creation framework. To enable co-creation processes, the skillset of the robot was extended with the ability to sense the physical fabrication environment and, driven by computational simulation routines, to suggest new solutions based on specific environmental performance criteria. The robotic system is thereby given the capacity to operate adaptively, allowing it to suggest new solutions and reject or alert about certain aspects of human-proposed design solutions.

Achieving human-robot co-creation processes will necessitate a discussion on the sharing of design intentions between human and robot. As with sharing design intentions between humans, this is likely to involve aspects of clear communication, willingness to compromise, and conflict resolution. The benefits include the opportunity to act creatively on several levels and to obtain and react upon feedback throughout an intertwined design and fabrication process. Incorporating human interaction during processes of robotic fabrication also suggests a potential resolvement to a particular machine-related challenge pointed out by Richard Sennett, in that "*Losing control leads to break down for machines, but discovery and happy accidents for people.*" (Sennett, 2008b). By integrating human interaction, we might establish explorative design processes to lose control intentionally without suffering machine break down. Through human intervention, robotic making can become more adaptable and more open towards happy accidents.

To reflect upon the impact that design methods for human-robot co-fabrication and co-creation might have on human creativity, human mental understanding and engagement, and bodily awareness, a closer examination of known issues related to modern machines, CAD software and design skills are beneficial. For this purpose, relevant observations and concerns expressed by Richard Sennett become relevant.

Regarding modern machines, Sennett argues that when misused, they can "*separate human mental understanding from repetitive, instructive, hands-on learning*" (Sennett, 2008), thereby depriving people of valuable learning processes. Amending this issue has been at the core of the design investigations and the human-robot design processes pursued throughout this thesis. In facilitating the integration of human, robot, material, and computational processes within an explorative design framework, the proposed co-creative design approach promotes repetition and hands-on learning as a shared and collaborative human-machine learning process. Human-robot design processes also hold the potential to restore the circular-metamorphosis (ibid., p.40) found in the repetitive cycle of drawing and making. The fast redrawing capabilities of CAD software has been considered to eliminate such circular processes and cause designers to put fewer considerations into their action. However, the implementation of robot-based design methods reinforces a parallel exploration of digital and physical design models, promoting a circular and repetitive process of hand drawing, CAD modelling, computational simulation, and robot-based material making. It can be further argued that the combination of CAD modelling and robot-based material fabrication, which enables a creative design exploration that alternate between two diverse design modalities, allows designers to shift between quick, less restrictive, geometry-based design explorations and slower, material-based design explorations restricted by the laws of physics. Based on the studies presented in this thesis, the deliberate alternations between diverse design modes can be regarded to support creativity by encouraging set-shifting, as described in section 3.1.2. The continuous shift between design modes forces human thought processes to adapt to new settings and gain new perspectives. Such transitions often result in our thought processes changing from a convergent perspective to a divergent perspective, allowing a shift towards new top-down processes based on different knowledge (Kandel, 2012).

The physical robot-based explorations of real-scale prototypes also address Sennett's concerns about CAD software and the hampering effects these screen-based interfaces might have on designers' ability to think in scale and appreciate material properties (Sennett, 2008). One might even argue that by actively engaging in both digital and physical processes of material making, a deep understanding of material properties and an embodied sense of scale is unavoidable.

7.5 Future explorations

The conclusions and reflections provided above has presented the achieved research results and discussed these through the conceptual framings around robotics and creativity. In this process, the discussion has hinted towards specific areas that, if subjected to further exploration and expansion, could have great significance for future work pursuing the creative potentials in human-robot co-creation and the emergence of joint cognitive systems for architectural design and fabrication. During the continuous development and advancement of methods for creative human-robot design exploration, a recurring discussion has revolved around the cognitive and technological challenges of working alongside a sensing robotic co-designer. The robot, equipped with design-specific abilities that in specific areas surpass that of the human designer, could extend the creative faculty of the joint human-robot design team. While some aspects of this discussion have been explored during this PhD project, others still need further investigation.

Artificial Intelligence

> *"Any notion of design that does not include learning is bound to be deemed unintelligent. In design, unlike in fields which rely on deductive processes, getting the same solution twice for the same problem is considered a failure." (Gero, 1991)*

One essential concern relates to the acquisition of new knowledge during engagement in explorative human-robot activities. Being the main reason for performing any type of experimental work, knowledge acquisition, and more specifically in this case, the storing and distribution of that knowledge between humans and robots acting in a joint cognitive system, is paramount for the future exploration and applicability of human-robot co-creation.

As concluded in Design Study 5, which explored human-robot co-creation in the context of robotic wood bending, if the robotic system does not learn from the collaborative exploration of a given problem or specific material system, the creative process will eventually lose momentum and stagnate. In such an explorative setting, the human designer will gradually gain more experiences, extending and adjusting existing knowledge. If the robotic system fails to achieve a similar learning process, the cognitive capacities within the joint human-robot system will only belong to the human, and the robot will remain to be just a tool – failing to act as an intelligent co-creator.

To achieve a collaborative and creative learning process with robots, it is therefore crucial that future explorations in human-robot co-creation investigate the potentials of artificial intelligence. Within the last decade, the implementation of AI, especially the sub-field related to machine learning, has started to infiltrate and influence architecture, design, and engineering disciplines. AI-powered design tools like Spacemaker (Spacemaker AI, 2021), Finch (Finch, 2021), and Higharc (Higharc, 2021) already support architects in their early design phases by automating repetitive tasks, generating and optimising spatial configurations, and allowing live analysis of building performance based on predictions instead of simulations. In robotic fabrication and material making processes, recent research has also showcased new opportunities for machine learning to *“extend the adaptation of design and fabrication information into the fabrication process*”, thereby *“establishing a continuing feedback loop between making and learning*” (Tamke, Nicholas and Zwierzycki, 2018).

For future explorations of AI-driven human-robot co-creation processes, it will be essential to investigate a fundamental problem shared by artificial intelligence and design. *“What needs to be known to design and how to get a computer to know it and use it?”* (Gero, 1991). This is not to say that the goal is to work alongside a robotic co-creator that shares the same design knowledge. On the contrary, when incorporating AI it is crucial to investigate the delegation of knowledge and skills within the human-robot team, ensuring divergent thinking through a stimulation of diverse associations and a shifting focus of attention. Designers learn from doing design. By utilising AI the robotic system can be equipped with comparable learning capabilities, allowing a parallel acquisition of design knowledge. Valuable data, either generated by the computational design system or captured by sensing devices, can be stored and redeployed throughout the explorative material-making process, thereby training the robot AI and facilitating a joint cognitive learning process.

In such creative human-robot design processes the robotic arm will become more than just a tool. It will become a collaborating partner with which we *“share authorship in the act of designing, evaluating and materialising architecture”*. (Wit et al., 2018)

Toolkits for human-robot co-creation

Based on experiences and practical insights gained through the construction and realisation of functioning human-robot design systems, a range of bespoke tools has been identified as critical for facilitating future research endeavours. The research studies presented in this dissertation relies on the author’s capacity to construct workable robotic systems and programme bespoke computational frameworks. In this process several existing software tools were utilised, but in some cases certain custom tools and processes had to be developed.

The main requirement for facilitating collaborative human and robotic actions is the establishment of a suitable architecture for human robot communication and interaction. While such an architecture was achieved through the development of a state machine model, working within the Grasshopper environment, the setting up and continuous administration of this communication workflow, did present an undesirable level of complexity. A complexity that increased concurrently with the number of human-robot interaction scenarios, greatly inhibiting the creative workflow. As the state machine model was found to be capable of supporting the desired HRI scenarios, a further advancement of more intuitive and user-friendly components for the Grasshopper environment, does present a promising research area. The necessity for ensuring that an integration of such tools occur within CAD environments, is based on the need for facilitating co-creation processes for which a high integration of design and fabrication models/processes are essential. The anticipation that human-robot co-creation processes should become accessible to a broad range of technology-minded architects, further supports development of such design-promoting HRI toolkits.

Another important requirement for the future advancement of human-robot co-creation processes is the opportunity to equip robotic arms with a broad variety of sensory devices and to allow access to the recorded sensor data through dedicated components within the parametric CAD environment. Such components could facilitate material making processes in which robots, informed by sensor data, are capable of adapting their actions and responding through automated actuation processes or using robotic gestures to propose possible design changes. In the presented research studies, such sensing of the robot's environment was achieved by utilising available Grasshopper add-ons for connecting with a Kinect Camera and by creating custom Grasshopper components that allowed for connection with an industrial laser distance sensor and a standard 4K web camera—the last requiring development of several additional components for visual analysis of image data. As with the HRI toolkits described above, the advancement of software add-ons that facilitate connection with robot sensors would facilitate an increased integration of design and fabrication processes. In this case, access to live sensory information can enable a highly feedback-driven design process providing enhanced insights concerning material performance and the changing conditions of dynamic fabrication processes.

Anthropomorphic communication

When engaging in robotic-based design explorations, a laptop or a teach pendant interface is often the preferred medium for communicating with the robot. While these screen-based interfaces have several useful features, there are several scenarios where the addition of more direct communication strategies would be advantageous. Likely examples are situations where the messiness of a fabrication environment or the need for full-body engagement in collaborative tasks makes screen-based interaction inconvenient or even impossible. In such cases, engaging in direct dialogue with the robot could enhance the collaborative process and support more intense, intimate and unfiltered interactions.

Design Study 3, 4, and 5 featured an exploration of different interaction and communication strategies, including physical interaction and manual manoeuvring of robots, recognition of hand gestures for controlling robot actions, and communication through robotic body language, also described as anthropomorphic communication. While there are several strategies and techniques for human-to-robot communication, such as computer-based devices (mice, keyboards, and joysticks), pushbuttons, motion sensors, speech recognition systems, touch sensors, etc., few options for robot-to-human communication exists. However, in scenarios that exclude or prohibit computer interfaces and teach pendants, the potentials in establishing communication through robotic body language are extremely interesting.

As presented in chapter 3.3.6, the ability for robotic arms to display anthropomorphic behaviour and communicate emotions to humans is currently being explored and has already shown great results. For the future advancement of creative human-robot collaboration, the potentials in anthropomorphic and gesture-based communication with robots are far-reaching. When the implementation of AI equips robots with learning capacities that allows it to generate design alternatives and suggest actions for possible improvements, robotic gestures could be the most intuitive method for informing humans about these design intentions. As experienced in the design studies, robotic gestures can also allow the robot to display its current state (idle, waiting, calculating, etc.) or indicate what it intends to do in the coming steps. Suggestion of design changes could for instance be conveyed by gesturing towards specific physical elements or areas of interest – deliberately redirecting the attention of the human designer. The future prospect of collaborating with a high precision robot equipped with the capacity to sense and learn from design explorations and communicate new design intentions through anthropomorphic gestures, would certainly have a creative impact on human-robot co-creation and future processes of human and robotic fabrication in architecture.

Evolve-on-site

Since the late 19th century, detailed working drawings, at that time in the form of blueprints, has acted as legal documents deciding, down to millimetre precision, the construction of architecture. At present, CAD and BIM software are used to continue this tradition, seeking to resolve forms in advance of their fabrication and later use (Sennett, 2008). In current architectural practice, industrialised and modernistic approaches to a large extent, neutralise local variations to diminish unforeseen challenges. The high precision and complex calculations of CAD and BIM can induce a blinding effect, hiding the actual quality and functionality of the finished work and lead to overdetermination (Sennett, 2008). Recently, issues regarding high precision and overdetermination in design planning have led to discussions of solve-on-site (SOS) principles (Scheurer, 2017). Here, parametric CAD modelling and digital fabrication afford a positive approach to the incomplete, allowing corrections and adaptations to occur during construction. By embracing unpredictability, design can respond to the dynamic nature of the building site and utilise the complexity of the site and the embodied knowledge of local craftsmen as a foundation for site-specific constructions. While the solve-on-site principle allows local adaptations and corrections during on-site fabrication, the approach is based on the expected solving of unexpected problems, aiming to realise the incomplete or imprecise designs as preconceived by the architect.

With future advancements of human-robot co-creation, there is an excellent opportunity for transferring the creative agency from the laboratory settings of early design explorations to the messy and dynamic context of the building site. Based on the implementation of multiple sensor technologies and advanced AI-driven learning capabilities, it is more than likely that robots will be capable of navigating the messy construction areas and support human craftsmen in performing daily tasks. When that day arrives, it is crucial to look past the apparent benefits of task automation and take advantage of the creative potential in human-robot co-creation. With architects embracing the incomplete and focusing on the specification of essential boundary conditions and desired performance requirements, the robot-assisted craftsman, in close collaboration with a robotic co-creator, could be given creative freedom to deploy embodied knowledge and material sensitivity in the fabrication of build architecture. Such intertwinement and sharing of design and fabrication activities will require a discussion of authorship. Who will be liable for the architectural expression, the building performance, or the material qualities? However, the deliberate incorporation of human and robotic actions will potentially improve the sensitivity and adaptability of the fabrication process without sacrificing the precision and alignment of individual building elements. And, most important, instead of solving problems on-site, humans and robots will collaborate in a creative strategy to ***evolve-on-site***.

References

Finch (2021). Available at: https://finch3d.com.

Gero, J. S. (1991) "Workshop on Ai in Design Ten Problems for Ai in Design."

Higharc (2021).

Kandel, E. R. (2012) *The age of insight: the quest to understand the unconscious in art, mind, and brain, from Vienna 1900 to the present*. New York: Random House.

Scheurer, F. (2017) *BIM to Fabrication (presentation slides)*. Available at: http://docplayer.org/106685126-Bim-to-fabrication-fabian-scheurer-stadt-aus-holz-megatrends-als-treibende-kraefte.html.

Schön, D. A. (1983) *The Reflective Practitioner - How Professionals Think in Action*. 1. edition. Basic Books.

Sennett, R. (2008) *The Craftsman*. London: Penguin Books.

Spacemaker AI (2021). Available at: https://www.spacemakerai.com.

Tamke, M., Nicholas, P. and Zwierzycki, M. (2018) "Machine learning for architectural design: Practices and infrastructure," *International Journal of Architectural Computing*, 16(2), pp. 123–143. doi: 10.1177/1478077118778580.

Wit, A. J. *et al.* (2018) "Artificial intelligence and robotics in architecture: Autonomy, agency, and indeterminacy," *International Journal of Architectural Computing*, 16(4), pp. 245–247. doi: 10.1177/1478077118807266.

Bibliography

Chapter 1: Introduction

Aish, R. and Hanna, S. (2017) "Comparative evaluation of parametric design systems for teaching design computation," *Design Studies*. Elsevier Ltd, 52, pp. 144–172. doi: 10.1016/j.destud.2017.05.002.

Bachelard, G. (2002) "Incisive Will and Solid Matter : The Aggressive Nature of Tools," in *Earth and the Reveries of Will - An Essay on the Imagination of Matter*. Dallas: The Dallas Institute Publications, pp. 27–47.

Bang, A. L. *et al.* (2012) "The Role of Hypothesis in Constructive Design Research," in *The Art of Research 2012: Making, Reflecting and understanding*. Helsinki, pp. 1–11. Available at: https://www.researchgate.net/publication/276264315_The_Role_of_Hypothesis_in_Constructive_Design_Research/citations.

Boden, M. A. (2004) *The Creative Mind: Myths and Mechanisms*. 2nd editio. London: Routledge.

Braumann, J., Stumm, S. and Brell-Çokcan, S. (2018) "Accessible Robotics," in Dass, M. and Wit, A. J. (eds) *Towards a Robotic Architecture2*. Applied Research and Design Publishing, pp. 154–165.

Brell-Çokcan, S. and Braumann, J. (2010) "A New Parametric Design Tool for Robot Milling," *Proceedings of the 30th Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA)*, pp. 357–363.

Brugnaro, G. and Hanna, S. (2019) "Adaptive Robotic Carving," in *Robotic Fabrication in Architecture, Art and Design 2018*. Cham: Springer International Publishing, pp. 336–348. doi: 10.1007/978-3-319-92294-2_26.

Brugnaro, G., Vasey, L. and Menges, A. (2008) "An Adaptive Robotic Fabrication Process for Woven Structures," in *ACADIA // 2016 Posthuman Frontiers: Data, Designers, and Cognitive Machines*, pp. 154–163. Available at: http://papers.cumincad.org/data/works/att/acadia16_154.pdf.

Dalsgaard, P. (2017) "Instruments of Inquiry: Understanding the Nature and Role of Tools in Design," *International Journal of Design*, 11(1), pp. 21–33. Available at: http://www.ijdesign.org/index.php/IJDesign/article/viewFile/2275/758.

Dass, M. and Wit, A. J. (2018) "Robotic Production in Architecture," in Dass, M. and Wit, A. J. (eds) *Towards a Robotic Architecture*. 1st edn. Novato: Applied Research and Design Publishing, pp. 28–61.

Doerstelmann, M. *et al.* (2015) "ICD/ITKE Research Pavilion 2014-15: Fibre Placement on a Pneumatic Body Based on a Water Spider Web," *Architectural Design*, 85(5), pp. 60–65. doi: 10.1002/ad.1955.

Dorst, K. and Cross, N. (2001) "Creativity in the design process: Co-evolution of problem-solution," *Design Studies*, 22(5), pp. 425–437. doi: 10.1016/S0142-694X(01)00009-6.

Dunn, N. (2012) *Digital Fabrication in Architecture*, *Computer*. doi: 10.1007/s00004-012-0130-8.

Edgar, B. L. (2008) "A Short Biography of KR150 L110," in Gramazio, F. and Kohler, M. (eds) *Digital Materiality in Architecture*. Lars Müller Publishers.

Gramazio, F., Kohler, M. and Willmann, J. (2014) *The Robotic Touch - How Robots Change Architecture*. 1st edn. Zurich: Park Books.

Jensen, M. B. *et al.* (2009) "Material Systems: A Design Approach," in *27th eCAADe Conference Proceedings*, pp. 721–728.

Jensen, M. B., Kirkegaard, P. H. and Holst, M. K. (2010) *A morphogenetic design approach with embedded structural analysis*, *Proceedings of the International Association for Shell and Spatial Structures (IASS) Symposium 2010*.

Kilian, A. (2006) *Design Explorations through Bidirectional Modeling of Constraints*. Available at: http://www.designexplorer.net/download/Kilian-phd-arch-2006.pdf.

Klinger, K. R. (2008) "Relations: Information Exchange in Designing and Making Architecture," in Kolarevic, B. and Klinger, K. R. (eds) *Manufacturing Material Effects: Rethinking Design and Making in Architecture*. New York: Routledge.

Leatherbarrow, D. (2005) “Architecture’s Unscripted Performance,” in Kolarevic, B. and Malkawi, A. M. (eds) *Performative Architecture - Beyond Instrumentality*. New York: Spon Press - Taylor & Francis, pp. 5–20.

Macdowell, P. and Tomova, D. (2011) “Robotic Rod-bending,” in *ACADIA 11: Integration through Computation [Proceedings of the 31st Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA)]*, pp. 132–137.

Menges, A. (2008) “Integral formation and Materialisation: Computational Form and Material Gestalt,” in Kolarevic, B. and Klinger, K. R. (eds) *Manufacturing Material Effects: Rethinking Design and Making in Architecture*. New York: Routledge.

Menges, A. (2015) “The New Cyper-Physical Making in Architecture,” *Architectural Design - Material Synthesis: Fusing the Physical and the Computational*, 85(05), pp. 28–33.

Menges, A. and Ahlquist, S. (2011) “Computational Design Thinking (Introduction),” in Menges, A. and Ahlquist, S. (eds) *Computational Design Thinking*. 1st edn. John Wiley & Sons, Inc., pp. 10–29.

Nakamura, J. and Csikszentmihalyi, M. (2005) “The Concept of Flow,” in Snyder, C. R. and Lopez, S. J. (eds) *Handbook of Positive Psychology*. 2nd edn. New York: Oxford University Press, pp. 89–105.

Nicholas, P. *et al.* (2015) “A Multiscale Adaptive Mesh Refinement Approach to Architectured Steel Specification in the Design of a Frameless Stressed Skin Structure,” in *Modelling Behaviour*. Cham: Springer International Publishing, pp. 17–34. doi: 10.1007/978-3-319-24208-8_2.

Nicholas, P. (2018) “Fabrication for Differentiation,” in Daas, M. and Wit, A. J. (eds) *Towards a Robotic Architecture*. 1st edn. Novato, CA: Applied Research and Design Publishing, pp. 76–87.

Oxman, R. (2008) “Digital architecture as a challenge for design pedagogy: theory, knowledge, models and medium,” *Design Studies*, 29(2), pp. 99–120. doi: 10.1016/j.destud.2007.12.003.

Pigram, D. and Mcgee, W. (2011) “Formation Embedded Design,” in *ACADIA 11: Integration through Computation [Proceedings of the 31st Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA)]*, pp. 122–131. Available at: http://papers.cumincad.org/data/works/att/acadia11_122.content.pdf.

Retsin, G., Garcia, M. J. and Soler, V. (2018) “Robotic Spatial Printing,” in Daas, M. and Wit, A. J. (eds) *Towards a Robotic Architecture*. Applied Research and Design Publishing, pp. 126–139.

Tedeschi, A. (2014) *AAD_Algorithms-Aided Design - Parametric strategies using Grasshopper*. 1st edn. Brienza: Le Penseur Publisher.

Terzidis, K. (2006) *Algorithmic Architecture*. Architectural Press, Elsevier. Available at: https://www.academia.edu/5003686/_009801309_architecture_ebook_algorithmic_architecture.

Vasey, L., Maxwell, I. and Pigram, D. (2014) “Adaptive Part Variation,” in *Robotic Fabrication in Architecture, Art and Design 2014*. Cham: Springer International Publishing, pp. 291–304. doi: 10.1007/978-3-319-04663-1_20.

Chapter 2: Research Design

Archer, B. (1995) “The Nature of Research,” *Co-design, Interdisciplinary journal of design*, pp. 6–13. Available at: https://archive.org/details/TheNatureOfResearch.

Bang, A. L. *et al.* (2012) “The Role of Hypothesis in Constructive Design Research,” in *The Art of Research 2012: Making, Reflecting and understanding*. Helsinki, pp. 1–11. Available at: https://www.researchgate.net/publication/276264315_The_Role_of_Hypothesis_in_Constructive_Design_Research/citations.

Dalsgaard, P. (2017) “Instruments of Inquiry: Understanding the Nature and Role of Tools in Design,” *International Journal of Design*, 11(1), pp. 21–33. Available at: http://www.ijdesign.org/index.php/IJDesign/article/viewFile/2275/758.

Dewey, J. (1938) *Logic - The Theory of Inquiry*. New York: Henry Holt and Company, Inc.

Dorst, K. (2011) “The core of ‘design thinking’ and its application,” *Design Studies*. Elsevier Ltd, 32(6), pp. 521–532. doi: 10.1016/j.destud.2011.07.006.

Frayling, C. (1993) "Research in Art and Design," *Royal College of Art Research Papers*, 1(1), pp. 1–5. Available at: http://researchonline.rca.ac.uk/384/3/frayling_research_in_art_and_design_1993.pdf.

Groat, L. and Wang, D. (2013) *Architectural Research Methods*. 2nd editio, *Architectural Research Methods*. 2nd editio. John Wiley & Sons, Inc.

Hacking, I. (1983) "The creation of phenomena," in *Representing and Intervening*. Cambridge University Press, pp. 220–232. doi: 10.1017/CBO9780511814563.017.

Koskinen, I. *et al.* (2012) *Design Research Through Practice*. Elsevier. doi: 10.1016/C2010-0-65896-2.

Krogh, P. G., Markussen, T. and Bang, A. L. (2015) "Ways of drifting—Five methods of experimentation in research through design," *Research into Design Across Boundaries*, 1, pp. 39–50. doi: 10.1007/978-81-322-2232-3_4.

de Landa, M. (2013) *Intensive Science and Virtual Philosophy*. Bloomsbury Academic.

Redström, J. (2011) "Some notes on program/experiment dialectics," in *Proceedings of Nordes'11 the 4th Nordic Design Research Conference, Making Design Matter!*, pp. 1–8.

Robertson, B. F. and Radcliffe, D. F. (2009) "Impact of CAD tools on creative problem solving in engineering design," *CAD Computer Aided Design*. Elsevier Ltd, 41(3), pp. 136–146. doi: 10.1016/j.cad.2008.06.007.

Roggema, R. (2016) "Research by Design: Proposition for a Methodological Approach," *Urban Science*, 1(1), p. 19. doi: 10.3390/urbansci1010002.

Yin, R. K. (2003) *Case study research - design and methods*. 3rd editio. London: SAGE Publications Inc.

Chapter 3: Fields and Domains

Aejmelaeus-Lindström, P. *et al.* (2016) "Jammed architectural structures: towards large-scale reversible construction," *Granular Matter*, 18(2), p. 28. doi: 10.1007/s10035-016-0628-y.

AIArtists.org (2021) *Sougwen Chung*. Available at: https://aiartists.org/sougwen-chung.

Aish, R. and Hanna, S. (2017) "Comparative evaluation of parametric design systems for teaching design computation," *Design Studies*, 52, pp. 144–172. doi: 10.1016/j.destud.2017.05.002.

Alvarez, M. E. *et al.* (2019) "Tailored Structures, Robotic Sewing of Wooden Shells," in Willmann, J. et al. (eds) *Robotic Fabrication in Architecture, Art and Design 2018*. Cham: Springer International Publishing, pp. 405–420. doi: 10.1007/978-3-319-92294-2_31.

Baartman, L. K. J. and de Bruijn, E. (2011) "Integrating knowledge, skills and attitudes: Conceptualising learning processes towards vocational competence," *Educational Research Review*, 6(2), pp. 125–134. doi: 10.1016/j.edurev.2011.03.001.

Bernal, M., Haymaker, J. R. and Eastman, C. (2015) "On the role of computational support for designers in action," *Design Studies*, 41, pp. 163–182. doi: 10.1016/j.destud.2015.08.001.

Boden, M. A. (2004) *The Creative Mind: Myths and Mechanisms*. 2nd editio. London: Routledge.

Braumann, J. and Brell-cokcan, S. (2015) "Adaptive Robot Control - New Parametric Workflows Directly from Design to KUKA Robots," in Martens, B. et al. (eds) *Proceedings of the 33rd eCAADe Conference*. Vienna University of Technology, Vienna, Austria, pp. 243–250. Available at: http://papers.cumincad.org/cgi-bin/works/Show?_id=ecaade2015_100&sort=DEFAULT&search=robot&hits=109.

Braumann, J., Stumm, S. and Brell-Çokcan, S. (2018) "Accessible Robotics," in Dass, M. and Wit, A. J. (eds) *Towards a Robotic Architecture2*. Applied Research and Design Publishing, pp. 154–165.

Brell-Çokcan, S. and Braumann, J. (2011) "Parametric Robot Control," *Proceedings of the 31st Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA)*, pp. 242–251.

Brell-Çokcan, S. and Braumann, J. (eds) (2013) *Rob | Arch 2012*. Vienna: Springer Vienna. doi: 10.1007/978-3-7091-1465-0.

Briggs, R. O. and Reinig, B. A. (2010) "Bounded ideation theory," *Journal of Management Information Systems*, 27(1), pp. 123–144. doi: 10.2753/MIS0742-1222270106.

Brugnaro, G. *et al.* (2016) "Robotic Softness: An Adaptive Robotic Fabrication Process for Woven Structures," in *ACADIA 2016: POSTHUMAN FRONTIERS: Data, Designers, and Cognitive Machines*.

Brugnaro, G. and Hanna, S. (2019) "Adaptive Robotic Carving," in *Robotic Fabrication in Architecture, Art and Design 2018*. Cham: Springer International Publishing, pp. 336–348. doi: 10.1007/978-3-319-92294-2_26.

Brugnaro, G., Vasey, L. and Menges, A. (2008) "An Adaptive Robotic Fabrication Process for Woven Structures," in *ACADIA // 2016 Posthuman Frontiers: Data, Designers, and Cognitive Machines*, pp. 154–163. Available at: http://papers.cumincad.org/data/works/att/acadia16_154.pdf.

Chung, S. (2019) *Why I draw with robots (TEDtalk)*. Available at: https://www.youtube.com/watch?v=q-GXV4Fd1oA.

Clifford, B. *et al.* (2014) "Variable Carving Volume Casting - A Method for Mass-Customized Mold Making," in Mcgee, W. and de Leon, M. P. (eds) *Robotic Fabrication in Architecture, Art and Design 2014*. Springer, pp. 3–15. doi: 10.1007/978-3-319-26378-6.

Csikszentmihalyi, M. (2014a) "Creativity and Genius: A Systems Perspective," in *The Systems Model of Creativity*. Dordrecht: Springer Netherlands, pp. 99–125. doi: 10.1007/978-94-017-9085-7_8.

Csikszentmihalyi, M. (2014b) "Society, Culture, and Person: A Systems View of Creativity," in *The Systems Model of Creativity*. Dordrecht: Springer Netherlands, pp. 47–61. doi: 10.1007/978-94-017-9085-7_4.

Csikszentmihalyi, M. (2014c) *The Systems Model of Creativity*. Dordrecht: Springer Netherlands. doi: 10.1007/978-94-017-9085-7.

Csikszentmihalyi, M. and Nakamura, J. (2006) "Creativity Through the Life Span from an Evolutionary Systems Perspective," in Hoare, C. (ed.) *Handbook of Adult Development and Learning*. New York: Oxford University Press, pp. 243–254. doi: http://www.oup.com.

Csikszentmihalyi, M. and Wolfe, R. (2014) "New Conceptions and Research Approaches to Creativity: Implications of a Systems Perspective for Creativity in Education," in *The Systems Model of Creativity*. Dordrecht: Springer Netherlands, pp. 161–184. doi: http://link.springer.com/10.1007/978-94-017-9085-7_10.

Darke, J. (1979) "The primary generator and the design process," *Design Studies*, 1(1), pp. 36–44. doi: 10.1016/0142-694X(79)90027-9.

Davis, D., Burry, J. and Burry, M. (2011) "The flexiblity of logic programming," in Herr, C. M. et al. (eds) *Circuit Bending, Breaking and Mending: Proceedings of the 16th International Conference on Computer-Aided Architectural Design Research in Asia*. Hong Kong: Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), pp. 29–38.

Dijksterhuis, A. and Meurs, T. (2006) "Where creativity resides: The generative power of unconscious thought," *Consciousness and Cognition*, 15(1), pp. 135–146. doi: 10.1016/j.concog.2005.04.007.

Doerstelmann, M., Knippers, J., Menges, A., *et al.* (2015) "ICD/ITKE Research Pavilion 2013-14: Modular Coreless Filament Winding Based on Beetle Elytra," *Architectural Design*, 85(5), pp. 54–59. doi: 10.1002/ad.1954.

Doerstelmann, M., Knippers, J., Koslowski, V., *et al.* (2015a) "ICD/ITKE Research Pavilion 2014-15: Fibre Placement on a Pneumatic Body Based on a Water Spider Web," *Architectural Design*, 85(5), pp. 60–65. doi: 10.1002/ad.1955.

Doerstelmann, M., Knippers, J., Koslowski, V., *et al.* (2015b) "ICD/ITKE Research Pavilion 2014-15: Fibre Placement on a Pneumatic Body Based on a Water Spider Web," *Architectural Design*, 85(5), pp. 60–65. doi: 10.1002/ad.1955.

Dörfler, K., Rist, F. and Rust, R. (2013) "Interlacing," in *Rob | Arch 2012*. Vienna: Springer Vienna, pp. 82–91. doi: 10.1007/978-3-7091-1465-0_7.

Dorst, K. and Cross, N. (2001) "Creativity in the design process: Co-evolution of problem-solution," *Design Studies*, 22(5), pp. 425–437. doi: 10.1016/S0142-694X(01)00009-6.

Dubor, A. *et al.* (2016) "Sensors and Workflow Evolutions: Developing a Framework for Instant Robotic Toolpath Revision," in Reinhardt, D., Saunders, R., and Burry, J. (eds) *Robotic Fabrication in Architecture, Art and Design 2016*. Cham: Springer International Publishing, pp. 410–425. doi: 10.1007/978-3-319-26378-6_33.

Dunn, N. (2012) *Digital Fabrication in Architecture*, *Computer*. doi: 10.1007/s00004-012-0130-8.

Elashry, K. and Glynn, R. (2014) "An Approach to Automated Construction Using Adaptive Programing," in McGee, W. and de Leon, M. P. (eds) *Robotic Fabrication in Architecture, Art and Design 2014*. Cham: Springer International Publishing, pp. 51–66. doi: 10.1007/978-3-319-04663-1_4.

Frank, F., Wang, S.-Y. and Sheng, Y.-T. (2015) *Taco ABB*. Available at: http://blickfeld7.com/architecture/rhino/grasshopper/Taco/ (Accessed: June 3, 2020).

Frith, C. (2007) *Making Up the Mind - How the Brain Creates Our Mental World*. Oxford: Blackwell Publishing.

Gannon, M. (2018) *Human-Centered Interfaces for Autonomous Fabrication Machines*. Available at: https://static1.squarespace.com/static/5758289d27d4bdf581e1c031/t/5b79b0bd88251b5c02217e90/1534701771028/2018-Gannon-Dissertation_Human-Centered_Interfaces_Autonomous_Fab.pdf.

García del Castillo Y López, J. L. (2019) *Enactive Robotics: An Action-State Model for Concurrent Machine Control*. Available at: http://nrs.harvard.edu/urn-3:HUL.InstRepos:41021631.

García del Castillo y López, L. J. (2019) "Robot Ex Machina," in *ACADIA // 2019 Ubiquity and Autonomy. Paper Proceedings of the 39th Annual Conference of the Association for Computer Aided Design in Architecture*, pp. 40–49.

Getzels, J. W. and Csikszentmihalyi, M. (1976) *The Creative Vision: a longitudinal study of problem finding in art*. New York: Wiley.

Gramazio, F., Kohler, M. and Willmann, J. (2014) *The Robotic Touch - How Robots Change Architecture*. 1st edn. Zurich: Park Books.

Guilford, J. P. (1967) *The Nature of Human Intelligence*. New York: McGraw-Hill.

Hakak, A. M., Biloria, N. and Venhari, A. A. (2014) "Creativity in Architecture—A Review on Effective Parameters Correlated with Creativity in Architectural Design," *Journal of Civil Engineering and Architecture*, 8(11), pp. 1371–1379. doi: 10.17265/1934-7359/2014.11.003.

Hektner, J. and Asakawa, K. (2000) "Learning to like challenges," in Csikszentmihalyi, M. and Schneider, B. (eds) *Becoming adult*. New York: Basic Books, pp. 95–112.

Hillier, B., Musgrove, J. and O'Sullivan, P. (1972) "Knowledge and Design," *Environmental Design: Research and Practice*, pp. 245–264.

Hinwood, D. *et al.* (2018) "A Proposed Wizard of OZ Architecture for a Human-Robot Collaborative Drawing Task," in Ge, S. S. et al. (eds) *International Conference on Social Robotics (ICSR 2018)*. Cham: Springer International Publishing (Lecture Notes in Computer Science), pp. 35–44. doi: 10.1007/978-3-030-05204-1_4.

Jeffers, M. (2016) "Autonomous Robotic Assembly with Variable Material Properties," in Reinhardt, D., Saunders, R., and Burry, J. (eds) *Robotic Fabrication in Architecture, Art and Design 2016*. Cham: Springer International Publishing, pp. 48–61. doi: 10.1007/978-3-319-26378-6_4.

Johns, R. L. (2014) "Augmented Materiality: Modelling with Material Indeterminacy," in *Fabricate 2014*. gta Verlag, Zurich, pp. 216–223. doi: 10.2307/j.ctt1tp3c5w.30.

Johns, R. L., Kilian, A. and Foley, N. (2014) "Design Approaches Through Augmented Materiality and Embodied Computation," in *Robotic Fabrication in Architecture, Art and Design 2014*. Cham: Springer International Publishing, pp. 319–332. doi: 10.1007/978-3-319-04663-1_22.

Jones, D. (2012) *The Aha! Moment: A Scientist's Take on Creativity*. Johns Hopkins University Press.

Kandel, E. R. (2012) *The age of insight: the quest to understand the unconscious in art, mind, and brain, from Vienna 1900 to the present*. New York: Random House.

Kandel, E. R. (2016) *Reductionism in art and brain science: bridging the two cultures*. New York: Columbia University Press.

Keating, S. *et al.* (2014) "A Compound Arm Approach to Digital Construction," in *Robotic Fabrication in Architecture, Art and Design 2014*. Cham: Springer International Publishing, pp. 99–110. doi: 10.1007/978-3-319-04663-1_7.

Kilian, A. (2006) *Design Explorations through Bidirectional Modeling of Constraints*. Available at: http://www.designexplorer.net/download/Kilian-phd-arch-2006.pdf.

King, N. and Grinham, J. (2013) "Automating Eclipsis," in *Rob | Arch 2012*. Vienna: Springer Vienna, pp. 214–221. doi: 10.1007/978-3-7091-1465-0_25.

Knippers, J. *et al.* (2015) "ICD/ITKE Research Pavilion 2012: Coreless Filament Winding Based on the Morphological Principles of an Arthropod Exoskeleton," *Architectural Design*, 85(5), pp. 48–53. doi: 10.1002/ad.1953.

Lawson, B. (2005) *How Designers Think - The Design Process Demystified*. 4th editio. Taylor & Francis.

Maher, M. lou (1994) "Creative design using a genetic algorithm," in Khozeimeh, K. (ed.) *Computing in Civil Engineering*. Nwe York: American Society of Civil Engineers, pp. 2014–2021.

Maher, M. and Tang, H.-H. (2003) "Co-evolution as a computational and cognitive model of design," *Research in Engineering Design*, 14(1), pp. 47–64. doi: 10.1007/s00163-002-0016-y.

Marzke, M. W. (1997) "Precision grips, hand morphology, and tools," *American Journal of Physical Anthropology*, 102(1), pp. 91–110. doi: 10.1002/(SICI)1096-8644(199701)102:1<91::AID-AJPA8>3.0.CO;2-G.

McGee, W. *et al.* (2017) "Infundibuliforms: Kinetic systems, Additive Manufacturing for Cable Nets and Tensile Surface Control," in *Fabricate 2017*. UCL Press, pp. 84–91. doi: 10.2307/j.ctt1n7qkg7.15.

McGee, W., Ng, T. Y. and Peller, A. (2019) "Hard + Soft: Robotic Needle Felting for Nonwoven Textiles," in *Robotic Fabrication in Architecture, Art and Design 2018*. Cham: Springer International Publishing, pp. 192–204. doi: 10.1007/978-3-319-92294-2_15.

Merleau-Ponty, M. (2013) *Phenomenology of Perception*. London: Routledge. doi: 10.4324/9780203720714.

Murphy, R. R. (2019) *Introduction to AI Robotics*. 2nd edn. Cambridge, MA: MIT Press.

Nakamura, J. and Csikszentmihalyi, M. (2005) "The Concept of Flow," in Snyder, C. R. and Lopez, S. J. (eds) *Handbook of Positive Psychology*. 2nd edn. New York: Oxford University Press, pp. 89–105.

Nicholas, P. *et al.* (2015) "A Multiscale Adaptive Mesh Refinement Approach to Architectured Steel Specification in the Design of a Frameless Stressed Skin Structure," in *Modelling Behaviour*. Cham: Springer International Publishing, pp. 17–34. doi: 10.1007/978-3-319-24208-8_2.

Oxman, R. (2006) "Theory and design in the first digital age," *Design Studies*, 27(3), pp. 229–265. doi: 10.1016/j.destud.2005.11.002.

Pazik, K. (2019) "Mockup Method: Heuristic Architectural Fragments as Central Models in Architectural Design," in Willmann, J. et al. (eds) *Robotic Fabrication in Architecture, Art and Design 2018*. Springer, pp. 31–43. doi: 10.1007/978-3-319-92294-2_3.

Peng, H. *et al.* (2018) "Roma: Interactive fabrication with augmented reality and a Robotic 3D printer," *Conference on Human Factors in Computing Systems - Proceedings*, 2018-April. doi: 10.1145/3173574.3174153.

Reinhardt, D. (2019) "Design Robotics - Towards human-robot timber module assembly," in *Architecture in the Age of the 4th Industrial Revolution - Proceedings of the 37th eCAADe and 23rd SIGraDi Conference*. São Paulo: Editora Blucher, pp. 211–216.

Robertson, B. F. and Radcliffe, D. F. (2009) "Impact of CAD tools on creative problem solving in engineering design," *CAD Computer Aided Design*, 41(3), pp. 136–146. doi: 10.1016/j.cad.2008.06.007.

Rowe, P. G. (1986) *Design Thinking*. Cambridge, MA: MIT Press. Available at: https://mitpress.mit.edu/books/design-thinking.

Rowe, P. G. (2017) *Design Thinking in the Digital Age*. Cambridge, MA: Harvard University Graduate School of Design and Sternberg Press.

Rutten, D. (2013) "Galapagos: On the logic and limitations of generic solvers," *Architectural Design*, 83(2), pp. 132–135. doi: 10.1002/ad.1568.

Sanders, E. B.-N. and Stappers, P. J. (2008) "Co-creation and the new landscapes of design," *CoDesign*, 4(1), pp. 5–18. doi: 10.1080/15710880701875068.

Saunders, A. and Epps, G. (2016) "Robotic Lattice Smock," in Reinhardt, D., Saunders, R., and Burry, J. (eds) *Robotic Fabrication in Architecture, Art and Design 2016*. Cham: Springer International Publishing, pp. 78–91. doi: 10.1007/978-3-319-26378-6_6.

Schön, D. A. (1983) *The Reflective Practitioner - How Professionals Think in Action*. 1. edition. Basic Books.

Schumann, K. and Johns, R. L. (2019) "Airforming - Adaptive Robotic Molding of Freeform Surfaces through Incremental Heat and Variable Pressure," in Haeusler, M., Schnabel, M. A., and Fukuda, T. (eds) *Intelligent & Informed - Proceedings of the 24th CAADRIA Conference - Volume 1*. Wellington, New Zealand, pp. 33–42. Available at: http://papers.cumincad.org/cgi-bin/works/paper/caadria2019_648.

Schwartz, T. (2013) "HAL: Extension of a visual programming language to support teaching and research on robotics applied to construction," in *Rob | Arch 2012*. Vienna: Springer Vienna, pp. 92–101. doi: 10.1007/978-3-7091-1465-0_8.

Sennett, R. (2008) *The Craftsman*. London: Penguin Books.

Søndergaard, A. *et al.* (2016) "Robotic Hot-Blade Cutting," in Reinhardt, D., Saunders, R., and Burry, J. (eds) *Robotic Fabrication in Architecture, Art and Design 2016*. Cham: Springer International Publishing, pp. 150–164. doi: 10.1007/978-3-319-26378-6_11.

Stumm, S., Devadass, P. and Brell-Cokcan, S. (2018) "Haptic programming in construction," *Construction Robotics*, 2(1–4), pp. 3–13. doi: 10.1007/s41693-018-0015-9.

Sutherland, I. E. (1963) *Sketchpad, a Man-machine Graphical Communication System*. Available at: https://dspace.mit.edu/handle/1721.1/14979.

Terzidis, K. (2006) *Algorithmic Architecture*. Architectural Press, Elsevier. Available at: https://www.academia.edu/5003686/_009801309_architecture_ebook_algorithmic_architecture.

UR (2020) *Universal Robots' Homepage*. Available at: https://www.universal-robots.com (Accessed: December 28, 2020).

Vasey, L. *et al.* (2016) "Collaborative Construction: Human and Robotic Collaboration Enabling the Fabrication and Assembly of a Filament-Wound Structure," in *ACADIA 2016: Posthuman Frontiers: Data, Designers, and Cognitive Machines - Proceedings of the 36th Annual Conference of the Association for Computer Aided Design in Architecture*. Ann Arbor, pp. 184–195. Available at: http://papers.cumincad.org/cgi-bin/works/paper/acadia16_184.

Vasey, L., Maxwell, I. and Pigram, D. (2014) "Adaptive Part Variation," in *Robotic Fabrication in Architecture, Art and Design 2014*. Cham: Springer International Publishing, pp. 291–304. doi: 10.1007/978-3-319-04663-1_20.

Visose (2016) *Robots - Grasshopper plugin for programming robots*. Available at: https://github.com/visose/Robots/ (Accessed: June 1, 2019).

Watson, T., Gobeille, E. and Hardeman, N. (2017) *Mimic*, *Design I/O*. Available at: https://www.design-io.com/projects/mimic (Accessed: December 7, 2020).

Woodbury, R. (2010) *Elements of Parametric Design*. 1st edn. Oxford: Routledge.

Wujec, T. (2017) *The Future of Making*. Melcher Media.

van Zak, J. *et al.* (2018) "Parametric Chemistry: Reverse-engineering Biomaterial Composite Structures for Robotic Manufacturing of Bio-Cement Structures across Scales," in Daas, M. and Wit, A. J. (eds) *Towards a Robotic Architecture*. Applied Research and Design Publishing, pp. 216–229.

Chapter 4: Informed Robotic Design Exploration

Bechthold, M. (2018) "Real-time Robotics," in Dass, M. and Wit, A. J. (eds) *Towards a Robotic Architecture*. Novato, CA: Applied Research and Design Publishing, pp. 114–125.

Brell-Çokcan, S. and Braumann, J. (2010) "A New Parametric Design Tool for Robot Milling," *Proceedings of the 30th Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA)*, pp. 357–363.

Foged, I. W. (2013) "Architectural Thermal Forms," in *Proceedings of the 31st eCAADe Conference*. Delft, pp. 99–105. Available at: http://cumincad.scix.net/cgi-bin/works/Show?ecaade2013_032.

Foged, I. W. and Jensen, M. B. (2018) "Thermal Compositions Through Robot Based Thermal Mass Distribution," in *Computing for a better tomorrow - Proceedings of the 36th eCAADe Conference*, pp. 783–790.

Foged, I. W., Pasold, A. and Jensen, M. B. (2014) "Evolution of an Instrumental Architecture," in *Fusion - Proceedings of the 32nd eCAADe Conference*, pp. 365–372. Available at: www.create.aau.dk.

Hauberg, J. (2011) "Research by design: a research strategy," *Architecture & Education Journal*, 1(2), pp. 1–11. Available at: http://recil.ulusofona.pt/handle/10437/2043.

Johns, R. L., Kilian, A. and Foley, N. (2014) "Design Approaches Through Augmented Materiality and Embodied Computation," in *Robotic Fabrication in Architecture, Art and Design 2014*. Cham: Springer International Publishing, pp. 319–332. doi: 10.1007/978-3-319-04663-1_22.

Koren, B. S. and Müller, T. (2017) "Digital Fabrication of Non-Standard Sound-Diffusion Panels in the large Hall of the Elbphilharmonie," in Menges, A. et al. (eds) *Fabricate 2017*. UCL Press, pp. 122–129.

Reinhardt, D. *et al.* (2016) "Towards a Micro Design of Acoustic Surfaces," in *Robotic Fabrication in Architecture Art and Design 2016*, pp. 136–149. doi: 10.1007/978-3-319-26378-6.

Santorso, K. *et al.* (eds) (2017) *Robotic Woodcraft - Towards the Craftmanship of the Future*. Vienna: University of applied Arts Vienna. Available at: http://www.roboticwoodcraft.com/wp-content/uploads/2019/04/RoboticWoodcraft.pdf.

Stasiuk, D. (2019) *Adaptive Parameterisation: Methods for employing flexible data structures for complex modelling practices in architectural design*.

Chapter 5: Interactive Robotic Design Exploration

Bermudez, J. and King, K. (1998) "Media interaction and design process: Establishing a knowledge base," in *Digital Design Studios: Do Computers Make a Difference? ACADIA Conference Proceedings*. Cincinnati, Ohio: Cumincad, pp. 6–25. Available at: https://cumincad.architexturez.net/doc/oai-cumincadworks-id-029f.

Boden, M. A. (2004) *The Creative Mind: Myths and Mechanisms*. 2nd editio. London: Routledge.

Foged, I. W. *et al.* (2016) *Bricks / Systems*. Edited by I. W. Foged. Aalborg University Press.

Maher, M. lou (1994) "Creative design using a genetic algorithm," in Khozeimeh, K. (ed.) *Computing in Civil Engineering*. Nwe York: American Society of Civil Engineers, pp. 2014–2021.

Murphy, R. R. (2019) *Introduction to AI Robotics*. 2nd edn. Cambridge, MA: MIT Press.

Pigram, D., Maxwell, I. and Mcgee, W. (2016) "Towards Real-Time Adaptive Fabrication-Aware Form Finding in Architecture," *Robotic Fabrication in Architecture, Art and Design 2016*, pp. 427–437. doi: 10.1007/978-3-319-26378-6.

Chapter 6: Co-creative Robotic Design Exploration

Hinwood, D. *et al.* (2018) "A Proposed Wizard of OZ Architecture for a Human-Robot Collaborative Drawing Task," in Ge, S. S. et al. (eds) *International Conference on Social Robotics (ICSR 2018)*. Cham: Springer International Publishing (Lecture Notes in Computer Science), pp. 35–44. doi: 10.1007/978-3-030-05204-1_4.

Murphy, R. R. (2019) *Introduction to AI Robotics*. 2nd edn. Cambridge, MA: MIT Press.

Nakamura, J. and Csikszentmihalyi, M. (2005) "The Concept of Flow," in Snyder, C. R. and Lopez, S. J. (eds) *Handbook of Positive Psychology*. 2nd edn. New York: Oxford University Press, pp. 89–105.

Pigram, D., Maxwell, I. and Mcgee, W. (2016) "Towards Real-Time Adaptive Fabrication-Aware Form Finding in Architecture," *Robotic Fabrication in Architecture, Art and Design 2016*, pp. 427–437. doi: 10.1007/978-3-319-26378-6.

Chapter 7: Conclusions

Finch (2021). Available at: https://finch3d.com.

Gero, J. S. (1991) "Workshop on Ai in Design Ten Problems for Ai in Design."

Higharc (2021).

Kandel, E. R. (2012) *The age of insight: the quest to understand the unconscious in art, mind, and brain, from Vienna 1900 to the present*. New York: Random House.

Scheurer, F. (2017) *BIM to Fabrication (presentation slides)*. Available at: http://docplayer.org/106685126-Bim-to-fabrication-fabian-scheurer-stadt-aus-holz-megatrends-als-treibende-kraefte.html.

Schön, D. A. (1983) *The Reflective Practitioner - How Professionals Think in Action*. 1. edition. Basic Books.

Sennett, R. (2008) *The Craftsman*. London: Penguin Books.

Spacemaker AI (2021). Available at: https://www.spacemakerai.com.

Tamke, M., Nicholas, P. and Zwierzycki, M. (2018) "Machine learning for architectural design: Practices and infrastructure," *International Journal of Architectural Computing*, 16(2), pp. 123–143. doi: 10.1177/1478077118778580.

Wit, A. J. *et al.* (2018) "Artificial intelligence and robotics in architecture: Autonomy, agency, and indeterminacy," *International Journal of Architectural Computing*, 16(4), pp. 245–247. doi: 10.1177/1478077118807266.

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