Environmental Tectonics

Matter Based Architectural Computation

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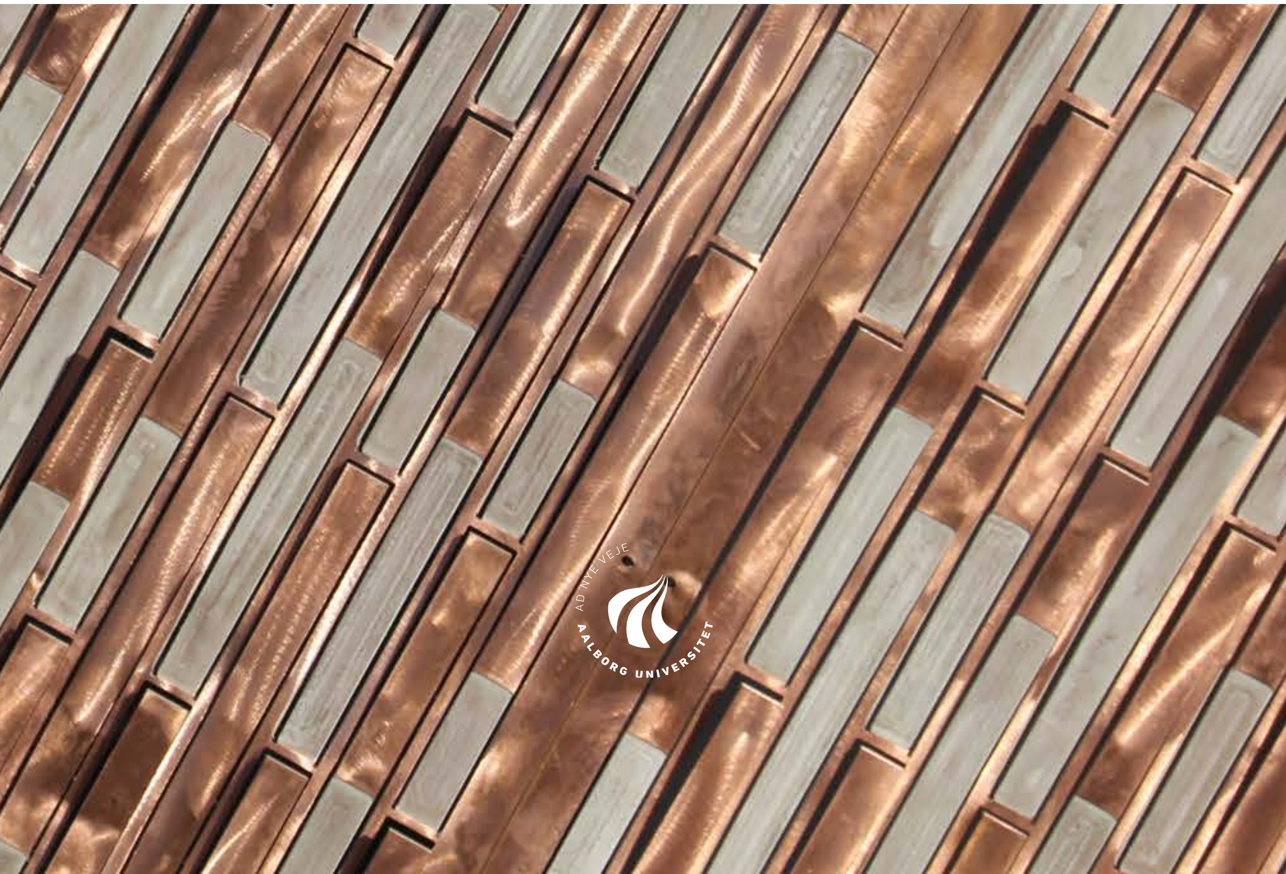

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Isak Worre Foged

PhD thesis submitted April 1, 2015

i. Colophon

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Author	Isak Worre Foged
PhD thesis submitted	April 1, 2015
Supervisors	Professor Mary-Ann Knudstrup Aalborg University Professor Dr. Michael U. Hensel Oslo School of Architecture
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This thesis has been submitted for assessment in partial fulfillment of the PhD degree. The thesis is partly based on the peer-reviewed submitted, accepted or published scientific papers which are listed below. Parts of the papers are used directly or indirectly in this thesis. As part of the assessment, co-author statements have been made available to the assessment committee and are also available at the Faculty. The thesis is not in its present form acceptable for open publication but only in limited and closed circulation as copyright may not be ensured.

ii. List of publications

Foged, I.W. (2015) *Constructing And Construing Environmental Sensations.* ICSA Conference Proceedings, Porto. (Submitted) [Part of chapter 3 and 4]

Foged, I.W., Pasold, A. (2015) *Thermal Responsive Envelope- Computational Assembling Behavioural Composites by Additive and Subtractive Processes.* Design Modeling Symposium 2015, Copenhagen. Springer Verlag (Accepted) [Chapter 13]

Foged, I.W., Pasold, A. (2015) *Development of a Method and Model for Programming Material Behaviour in a Responsive Envelope*. eCAADe Conference Proceedings 2015, Wien. (Accepted) [Chapter 12]

Foged, I.W. (2015) *Finding Thermal Forms.* New Tectonics Beyond New Technologies. Aalborg University Press. (Submitted) [Chapter 11]

Foged, I.W., Brath, M. (2015) *The Nature of Architectural Experiments*. Open Source City - Capturing the Platform4 Experience. Aalborg University Press (Accepted) [Part of chapter 2]

Foged, I.W. et al. (2014) *Evolution of an Instrumental Architecture.* eCAADe Conference Proceedings 2014, Delft, p. 365-372 (Published) [Chapter 8]

Foged, I.W. (2013) *Architetcural Thermal Forms II.: Brick Envelope*.CAAD Futures 15th Conference Proceedings 2013, Shanghai, p. 327-337. Springer. (Published) [Chapter 10]

Foged, I.W. (2013) *Architectural Thermal Forms.* eCAADe Conference Proceedings 2013, p. 99-105 (Published) [Chapter 9]

Foged, I.W. (2012) *Architectural Metabolic Forms.* Nature and Design Conference Proceedings 2013, WIT Transactions on Ecology and the Environment, Vol. 160, p. 107-117. (Published) [Pre-study for chapter 9]

Foged, I.W., et al. (2012) *Acoustic Environments - Applying Evolutionary Algorithms for Sound Based Mophogenesis*. eCAADe Conference Proceedings 2012, Prague, p. 347-353. (Published) [Chapter 7]

Foged, I.W. (2012) *On Tectonic Terms*. On Tectonic Terms. Aalborg University Press, p. 25-37. (Published) [Part of chapter 4]

iii. Resume (da.)

Denne PhD afhandling undersøger miljøbaserede arkitektoniske konstruktioner igennem teori og arkitektureksperimenter. Gennem studier af tre primære arkitekturteoretiske felter, Bæredygtig Arkitektur, Tektonik i Arkitekturen og Digital Arkitektur, fokuserer afhandlingen på at formulere et teoretisk og instrumentelt grundlag for en menneske-orienteret bæredygtig arkitektur, formuleret som 'Environmental Tectonics'.

Integrationen af de tre felter tager udgangspunkt i forsøget på at adressere arkitekturens rolle i forhold til de menneskelige, klimatiske og konstruktionsmæssige aspekter. Denne ramme positionerer menneskets sansning af miljøet som det centrale aspekt og det grundlæggende element i forhold til opbygningen af nye arkitektoniske metoder og modeller. Forskningen er baseret på de potentialer der fremkommer når de tre arbejdsfelter overlappes of sammenflettes. Som en konsekvens af dette, fremkommer der en kritisk positionering i forhold til den nutidige tilgang i det byggede miljø, som i overvejende grad forsøger at isolere bygninger og mennesker fra deres lokale miljøer frem mod energieffektivitet i byggeriet.

Igennem observationer, litterære studier, case studier og elementære eksperimenter, undersøger og opbygger afhandlingen det teoretiske fundament for en tilgang til arkitekturen der integrerer de dynamiske aspekter i både designprocesser og i arkitektoniske konstruktioner. Disse studier undersøger hvordan mennesker opfatter deres miljø og hvordan miljøer skabes kontinuerligt. Den fremkomne indsigt fra disse studier former argumentet for at organiseringen af 'matter' er den principielle underlæggende model for skabelsen af æstetisk arkitektur, som reciprokt argumenteres for at være miljømæssig bæredygtig. Udfra disse studier formuleres otte arkitektoniske metodetilgange, som har til hensigt at være både deskriptive og præskriptive i henhold til afhandlingens målsætning.

Som en del af de ovennævnte undersøgelser og diskussioner arbejdes der igennem designforskningsstudier baseret på computerbaserede eksperimenter, i både digitale of fysiske prototyper. De digitale metoder og modeller er baseret på simuleringsprocesser, som primært fokuserer på evolutionssimuleringer, og akustiske og termiske simuleringer. De fysiske prototyper er skabt parallelt med de digitale prototyper for at demonstrere, teste og avancere de foreløbige metodeforslag baseret på de teoretiske studier. På den måde anvendes designforskningsstudierne som metode til at udvide og klargøre formuleringerne af de teoretiske forslag, som samlet udgør rammen for Environmental Tectonics.

De empiriske og teoretiske studier var udviklet i et reciprokt forhold, med henblik på en bedre forståelse for hvorfor og hvordan vi kan konstruere miljøer for mennesker og hvad der er nødvendigt for at disse kan muliggøres igennem arkitekturens virkemidler. Det empiriske indhold er baseret på det litterære materiale, case studie materiale og data materiale fra digitale simuleringsprocesser, elementære studier og fuldskala arkitektoniske prototyper.

Baseret på de ovenstående undersøgelser er den tværfaglige arkitektoniske ramme præsenteret, hvilket bidrager med specifikke teoretiske og instrumentelle koncepter, metoder og modeller der har som mål at formulere ny viden omkring en ontologisk forståelse af miljøbaserede arkitekturkonstruktioner.

iv. Abstract (eng.)

This PhD thesis examines environmental architectural constructions through theoretical studies and design experiments. Through the study of three primary fields in architecture, namely Environmental Architecture, Tectonics in Architecture and Computational Architecture, the thesis focuses on formulating a theoretical and instrumental framework for a human-oriented, environmentally sustainable architecture, entitled ‘Environmental Tectonics’.

The integration of these three fields is pursued in an attempt to address the role of architecture in relation to human, climatic and constructional concerns. This approach positions the human sensation of an environment as a central aspect and the basis for new architectural construction methods and models. The research is pursued on the potentials of overlaying and interweaving the three fields. In turn, the thesis takes a critical position to the contemporary approach in the built environment, which increasingly intensifies the isolation of buildings and humans from their local environment in the interest of energy efficiency.

Through observations, literary studies, case studies and elementary experiments conducted, the thesis explores and constructs the theoretical foundation for an approach to architecture that integrates the dynamic aspects of building, both in design processes and in constructed architectures. These studies explore how humans perceive their environment and how environments are continuously constructed. Insights from these studies form the argument of matter organisation as the principle model for the construct of aesthetic architectures that in reciprocity are argued to be inherently environmentally sustainable. From these studies, eight architectural design propositions are formulated, which are aimed at being both descriptive and prescriptive in relation to the thesis objective.

As part of the above examinations and discussions, research-by-design studies are conducted through computational experiments based on both digital and physical probes. The digital computational methods and models are based on simulation processes, focused primarily on evolutionary simulation and acoustic and thermal environmental simulations. Physical probes are constructed through the development of the digital probes to demonstrate, test and advance the provisional theoretical propositions. As a result, the design research studies serve to further orient the formulation of the theoretical propositions that are offered as the framework for Environmental Tectonics.

The empirical and theoretical work was developed in a reciprocal relationship oriented towards a better understanding of why and how we can construct environments for humans and what is required for these environments to be pursued through architectural means. The empirical content is based on the population of theoretical material, case study material and data material from computational simulation processes, elementary studies and full-scale architectural probes.

On the basis of the above inquiries, the interdisciplinary architectural framework presented contributes with specific theoretical and instrumental architectural concepts, methods and models that aim to form an extended epistemology on the ontology of architectural environmental constructions.

v. List of contents

i. Colophon 5
ii. List of publications 7
iii. Resume (da.) 9
iv. Abstract (eng.) 11
v. List of content 13
vi. Preface 19
vii. Chapter content 25

Part 1: Foundation

Chapter 1: Introduction

1.0 Preliminary 35
1.1 Motivation 35
1.2 Four Approaches 39
1.3 Problem framing and statement 46
1.4 Initiating questions 47
1.5 Theoretical Platform 48
1.6 Objective 51
1.7 Three Fields 51
1.8 Synthesis 65
1.9 Hypothesis and Question 66

Chapter 2: Methodology

2.0 Preliminary 71
2.1 Research span 71
2.2 Research position 73
2.3 Research Design 75
2.4 Verification, Falsification and Phenomenon 88
2.5 Conclusion 89

Part 2: Fields

Chapter 3: Environments

3.0 Preliminary 95
3.1 Notes on Environments 96
3.2 Material 115
3.3 Energy 121
3.4 Modelling Environments 125
3.5 Synthesis, Conclusions and Propositions 134

Chapter 4: Tectonics

4.0 Preliminary 139
4.1 Notes on Tectonics 140
4.2 Addition 151
4.3 Transformation 163
4.4 Membrane 175
4.5 Synthesis, Conclusions and Propositions 181

Chapter 5: Computation

5.0 Preliminary 187
5.1 Notes on Computation 188
5.2 Machine Computation 195
5.3 Material Computation 212
5.4 Hybrid Computation 217
5.5 Synthesis, Conclusions and Propositions 222

Chapter 6: Correlations

6.0 Preliminary 227
6.1 Aesthetics 227
6.2 Organisation 229
6.3 Evolution 232
6.4 Synthesis and Conclusions 233

Part 3: Probes

Chapter 7: Acoustic Tectonics I

7.0 Preliminary 239
7.1 Methods and Models 241
7.2 Design experimentation 243
7.3 Results 247
7.4 Conclusions 247
7.5 Discussion 251

Chapter 8: Acoustic Tectonics II

8.0 Preliminary 257
8.1 Methods and Models 259
8.2 Design experimentation 265
8.3 Results 265
8.4 Conclusions 267
8.5 Discussion 271

Chapter 9: Thermal Tectonics I

9.0 Preliminary 277
9.1 Methods and Models 279
9.2 Design Experimentation 283
9.3 Results 285
9.4 Conclusions 287
9.5 Discussion 287

Chapter 10: Thermal Tectonics II

10.0 Preliminary 293
10.1 Methods and Models 297
10.2 Design Experimentation 301
10.3 Results 303
10.4 Conclusions 305
10.5 Discussion 309

Chapter 11: Thermal Tectonics III

11.0 Preliminary 313
11.1 Methods and Models 315
11.2 Design Experimentation 321
11.3 Results 325
11.4 Conclusions 325
11.5 Discussion 328

Chapter 12: Thermal Tectonics IV

12.0 Preliminary 333
12.1 Methods and Models 337
12.2 Design Experimentation 343
12.3 Results 345
12.4 Conclusions 345
12.5 Discussion 347

Chapter 13: Thermal Tectonics V

13.0 Preliminary 353
13.1 Methods and Models 355
13.2 Design Experimentation 357
13.3 Results 359
13.4 Conclusions 361
13.5 Discussion 361

Part 4: Conclusions

Chapter 14: Synthesis

14.0 Preliminary 371
14.1 Research field associations 371
14.2 Research field boundaries 379

Chapter 15: Conclusions

15.0 Preliminary 387
15.1 Revisiting from the beginning 387
15.2 Environmental Tectonics – An Architectural Framework 389
15.3 Answering and Restating Research Questions 393
15.4 Contributions 398
15.5 Conclusions 399
15.6 Reflections on Methods and Results 400
15.7 Future studies 403

Bibliography 405
List of figures 433

vi. Preface

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This thesis must begin with an acknowledgment of the many people who have made this work possible. In chronological order: The former head of the Institute at Architecture & Design, Aalborg University, Michael Mullins, offered a generous, fully financed PhD stipend inside a well-established yet flexible doctoral programme, open to architectural research within environmentally sustainable architecture. The open frame and unrestricted conditions of the PhD stipend presented an opportunity seldom offered in an academia that increasingly seems to be bound by rigid, strategic research programmes. I would like to thank the Institute for this call and for allowing me to pursue my research interests within this open context. This frame also offered me the opportunity to freely choose Professor Mary-Ann Knudstrup and Professor Dr. Michael Hensel as my two thesis supervisors.

Professor of sustainability and head of SARC (Research group for Sustainable Architecture at AAU) Mary-Ann Knudstrup, of Aalborg University, has, through her insight into environmental sustainable architecture, its processes, formal demands, parallel development in engineering and architecture and current challenges, informed the project greatly. Her engagement and continuous considerations of grounding terminology when merging theoretical fields have helped to make the arguments more readable across different field terminologies, effectively making this document more accessible to a broader audience.

Professor Dr. Michael Hensel, head of RCAT (Research Centre for Architecture and Tectonics at AHO) from the Oslo School of Architecture, and chairman of the research association OCEAN, has influenced almost all aspects of this thesis. I do not recall a single meeting in which I did not return to my work with a multitude of new sources and connections, questions on research and new insights into the subjects of inquiry. Michael Hensel has been a constant source for inspiration and a source to other people to whom he has unselfishly connected me.

It is difficult to estimate the impact of thesis supervision, but the choice of supervisors at the beginning of the project has proved tremendously fruitful for this work. Looking back, there is much more than the above to thank both Mary-Ann Knudstrup and Michael Hensel for.

In the immediate research context at Aalborg University, I have had continuous discussions and research collaborations with Esben Bala Poulsen, Mads Brath and Lasse Andersson. Esben has an incredible impulse and intuitive engagement from which I have received both energy and ideas. Mads has become a permanent partner in teaching computational architecture and a frequent research colleague. His calm yet engaged attitude and analytical focus on both solutions and problems encourage my own work. Lasse, who now is the Head of Exhibitions at the Utzon Center in Aalborg, has increasingly become a colleague with whom I have discussed forms of research tendencies and their specific dissemination. This has helped me to channel and support design research and open contexts of research discussions that would not otherwise be possible.

At Aalborg University, I also had the benefit of being directly connected to researchers working on assessment of thermal and indoor simulations. Research Assistant Jesper Nørgaard and Assistant Professor Jerome Le Dreau have been particularly helpful in guiding to mathematical models and relevant studies within this field.

I have, from the beginning, seen the project platform as being rooted in a network of people at different academic institutions. For this reason, I have actively sought discussion with the knowledgeable and skilled researchers at CITA (Centre for IT and Architecture at the Copenhagen School of Architecture). In turn, they have invited me on several occasions to take part in teaching research reviews and research seminars and offered to present and discuss my work. Specifically, I would like to thank the head of CITA, Professor Mette Ramsgaard Thomsen, and the head of CITA Studio, Associate Professor Phil Ayres, as well as Associate Professor Martin Tamke and Assistant Professor Paul Nicholas, for many inspiring conversations and constructive points of critique in relation to my work.

As part of my stipend, I was offered an exchange period at an academic institution. I contacted Professor Kenneth Frampton at GSAPP, Columbia University, and spent the autumn semester of 2014 at Avery. The high academic honour that Professor Frampton receives across the architectural discipline is for a reason. Through many conversations on tectonics in architecture, building culture and culture in general, I received ideas and critique, which I did not imagine at the outset of this thesis work. I am incredibly thankful to Kenneth Frampton, firstly, that he invited me to Columbia University after my initial contact, secondly for his inspiring energy for architecture and its need for humanism, and lastly for connecting me to exceptional researchers at Princeton University for conversations related to my research, namely Associate Professor Spyros Papapetros, Assistant Professor Axel Kilian, Assistant Professor Forrest Meggers and Assistant Professor Sigrid Andrianssens.

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Master mason Kim Schmidt Pedersen from the Technical College Aalborg and his students did an incredible job building the Thermal Tectonics II probe presented in chapter 10, which stood for almost a year before it was removed. Master mason Jan Drejer and his students are currently in the process of building the Thermal Tectonics III probe presented in chapter 11. Conversations with these knowledgeable and skilled people have added applied layers to the research projects otherwise impossible without them.

Bjarne Juul Andersen from Mefa Nordic not only manufactured the physical prototypes for the studies presented in chapter 12 but also engaged in discussions on various materials' thermal behaviour and the relation to manufacturing constraints.

In a similar manner, Kent Pedersen from W. Olesen & Søn manufactured the dynamic prototype modules presented in chapter 13, and offered empirical advice on manufacturing constraints and possibilities in relation to future composite models. It goes without saying that this interdisciplinary thesis in architecture has advanced significantly through a direct knowledge transfer between academic research and practice.

For the above research exchange, research probes and research presentations to be possible, I have, besides the support from Aalborg University, been privileged to receive financial means from a series of foundations in Denmark. I am grateful for the support of the Realdania Foundation, the COWI Foundation, Knud Højgaard's Foundation and the Oticon Foundation. Without these contributions, four of the full-scale probes could not have been realised, nor could I have had the long research period at Columbia University.

From the background comes the most solid support. I must thank my parents, Eva and Erik, for providing unconditional support while still posing engaging and intriguing questions on all parts of this work. To my brothers, Kasper and Jakob, who by all means span the creative field, from complex mathematics-based engineering in autonomous systems via music to the creation of award-winning animation movies. Kasper, in addition, installed the sensor network registering thermal conditions in the last research experiment in chapter 13. In truth, I draw both support and inspiration from my family.

And finally, to my Anke, my partner in life, in research and in practice and now mother to our wonderful baby daughter Kira. You relentlessly support, modify and expand my world. Your contributions to this work are directly visible in several co-authored peer-reviewed papers, yet the impact is invaluable and cannot be measured. I am deeply grateful for all aspects that you add to my work and life.

Isak Worre Foged
March, 2015

Reading the thesis

The dissertation is structured in four parts: Foundation, Fields, Probes and Conclusion. The first part constructs the basis for the research project. The second and third parts construct the main arguments and empirical work. The fourth part concludes based on the previous three parts and points to possible future studies. The dissertation is structured linearly, but the three main chapters in Fields are, in reality, parallel paths of theory building. In a similar way, the design research experiments in Probes are created with some overlapping and interweaving. An expanded list of chapter contents is located on pages 25-30.

Large parts of the dissertation have been published in peer-review conference proceedings, journals or anthologies. The references to these publications are listed at the beginning, on page 7, and after each respective chapter related to a publication.

The dissertation is illustrated with photos, diagrams, drawings and graphs. These are referred to in the main text and accompanied with captions. A few of the figures have been advanced with an augmented reality layer [AR], allowing a reading of the dynamics inherent in the figure beyond the printed version. The augmented layer is created with the programme Layar and is accessible through the Layar app for smartphones. To access the dynamic reading, please install the app and scan the figures that are listed to include the augmented information.

The bibliography is situated at the end of the thesis, structured in chapters. This means that some literary sources overlap occurs between chapters. This has been accepted, as some references are long papers and books with multiple arguments and diverse contents. Specifying the relation to the chapter is intended to make the literature more accessible for the reader. A full list of figures is located after the bibliography.

vii. Chapter content

Chapter 1: Introduction

The introduction chapter intends to construct the initial background for the research project and form a first delineation of thematic and instrumental approaches. As a starting point, a brief motivational note is included. This serves to position and orient the research project against the four approaches to environmentally sustainable architecture subsequently presented: Passiv Haus, Zero-Energy Buildings, Free-Running Buildings and Performance-Oriented Architecture. The intent is not to convey an exhaustive analysis of the four approaches, but to point to ongoing research activities related to this work. In this process points of critique are raised that subsequently form the basis of indeterminate aspects and initiation of research questions. These questions then point to the general problem framing, problem statement and objective of the dissertation. Following the problem and objective framing, the theoretical platform for Environmental Tectonics is outlined, enabling a formulation of the core research agenda. This delineates the work further into three principal thematic fields investigated throughout the project, these being Environmental Architecture, Tectonics in Architecture and Computational Architecture. An initial outline of these research fields will then be conducted, enabling both a synthesis and provisions of relevant indeterminate aspects to be pursued. This then leads to the overall hypothesis and research question of the project.

Chapter 2: Methodology

The methodology chapter intends to clarify and argue for the approach to research taken within the thesis by elaborating on an architectural research methodology that is based on the objective of the thesis. Environmental sustainable architecture, with its broad scope, can be understood differently from the perspective of natural and engineering sciences' intense delimiting into quantitative isolated research inquiries and from the humanistic perspective of inclusive qualitative inquiries. The research design approach is therefore broad in character. However, there is a need for specificity to allow concrete methods of testing, as is central to scientific production. With this in mind, a research position is stated, which is advanced into a research design. The research design integrates methods and models from the sciences and humanities, with the attempt to address the two objectives of the project being an overall architectural theoretical framework and a specific set of applied methods and models. The outline of the research methods illustrates a mixed-model approach, including theoretical-conceptual research into design, methodological-instrumental research for design and experimental-hypothetical research through design. Specific research inquiries within the thesis are approached according to the research method considered most suitable.

Chapter 3: Environment

This chapter intends to discuss, clarify and formulate concepts of environments accessible to an Environmental Tectonic approach. While Free Running Buildings and Performance-Oriented Architecture approaches are currently advanced, it is in the Introduction chapter discussed how architectural research and practice is centred on an energy-efficiency-based approach to environmentally sustainable architecture. This points to an increasing adoption of technically oriented methodologies, rather than a human environment-oriented, architectural methodology. From this position, an initial question is posed that frames why and how environments for humans are constructed by asking: Why and how can environmental constructions enrich human-perceived environments? The question is addressed in this chapter, particularly in the section Notes on Environments, by analysing and elaborating upon theories rooted in biological, neurological and architectural domains. The intention of this section is to get closer to an understanding of why and how we perceive and approach environmental constructions for humans, as a prerequisite for an environmentally sustainable architecture. Following this examination, the chapter proceeds towards offering an instrumental approach to the notions above and how they can be integrated into architectural design models by asking: How can analytical and numerical methods of human sensations of the environment be integrated into the architectural conceptual design phase? These questions are addressed in the sections Material and Energy and in particular in the section Modelling Environments, rooted in theories from biological, engineering and architectural domains. The intention of these sections is to get closer to ways of implementing the intended architectural environments into form exploration and form analysis methods and models, which will be advanced further in the chapters Tectonics and Computation.

Chapter 4: Tectonics

The chapter will firstly locate the etymological and theoretical foundation of tectonics in architecture. The reason for this is to search for the meaning of how the construction end effect receives the term and notion of ‘tectonic’. To approach and exemplify the question, an examination of the work of one architect in particular is conducted, following the chosen case study methodology. This gives an inroad to the subsequent sections of Addition and Transformation, which investigate in greater detail and position specific operations with the aim of supporting a more detailed methodological design approach in response to the thesis objective. These sections are then followed by an attempt to position the foremost endeavour for an Environmental Tectonic approach in the section on Membrane. This section specifically points back to the theoretical discussion of the previous chapter, Environments, and forward in terms of positioning the architectural probes in Probes (part 3) of this thesis. Following the theoretical foundation, which takes place through exemplification and advocated operations, lastly, a set of propositions is suggested to move tectonics into a prescriptive and contextual instrumentality in architecture towards the extension, Environmental Tectonics. The chapter also serves as a basis to approach a computational methodology adhering to the conclusions of both this and the previous chapter in the following chapter, entitled Computation.

Chapter 5: Computation

Following the research methodology of etymological grounding, the chapter begins with discussing computational notions that construct the platform from which we can suggest methods and models for an Environmental Tectonics approach. While the first section may appear to be of a historical character, it attempts to illustrate the notion that computation was, in its infancy, occupied with similar issues to those pursued in this thesis, though for different reasons. This section is followed by the two computational orientations of Machine-based computation and Material-based computation, relating the previous propositions to computation. To integrate and further advance these computational methods, Hybrid computational models are suggested. These are based upon related work in other scientific fields and are pursued to address the objective of the thesis and the questions that have arisen throughout the dissertation. Based on these discussions, an additional set of propositions is formulated as the basis for design research experiments.

Chapter 6: Correlations

The previous three chapters began with an etymological and field-specific prolegomenon based on the objective and research questions described in the Introduction chapter. By identifying, examining and formulating a theoretical argument and answers within each field, a series of propositions have been offered as a basis for Environmental Tectonics. Within the chapters, inter-field relationships have been identified and, moreover, elaborated upon through theoretical arguments and case-based examples. With the attempt to further specify and elaborate upon these relationships and extend the answers given, three aspects that are identifiable by correlation are further discussed. These aspects are emphasised to partially conclude, advance, explore and clarify the tentative grounding of the theoretical and instrumental framework. The three core aspects forming the expanded formulation for Environmental Tectonics, are referred to as Aesthetics, Organisation and Evolution.

Chapter 7: Acoustic Tectonics I

It is attempted in this chapter to create a design method that combines simulation methods, assessing two acoustic properties driven by evolutionary processes. Additionally, rather than developing an architecture based on one sound source, as is common in concert halls and lecture halls, the study includes four sound emitters that, in combination, are the source for the sound environment. To allow a combination of global articulation and local differentiation based on elements and their joint formation, a parametric model is created that integrates both sound simulations and evolutionary simulations. The chapter presents methods and models based on the Element, System, Formation instrumentality, sound-perceived environmental simulations and progressive design development based on genetic algorithms. From a series of studies based on this experimental setup, results from this approach are presented, followed by conclusions and discussion.

Chapter 8: Acoustic Tectonics II

What is attempted in this chapter is to formulate a method and model in which classical musicians can use architecture as an extension of their instruments. This is approached by using evolutionary algorithms to search for an environmental-material organisation that allows the musician to change the acoustic environment by changing his position within it, so that the environment becomes instrumental for the musician based on her spatial positioning. The study presents a parametric model, a sound environment simulation model and an evolutionary model. The combination of these models allows the development of a digital and 1:1 physical probe, which investigate the notions of environmental constructions as formulated in part two.

Chapter 9: Thermal Tectonics I

It is attempted in this chapter to create a generative algorithm that, through additive processes, constructs building forms that are based on the solar climatic environment. The potential is to increase the exergetic capacity of the building for further possibilities of articulating the thermal environment directly perceived by humans. By this process, it is attempted to reveal the relationship between the environmental influence of the sun and the additive construction process. The study presents a generative method and a model based on a generative rewriting algorithm, which explicitly connects the generated building forms to the climatic environment based on solar-earth-matter relations. Specifically, the presented study investigates the capacity to create environmentally sustainable architectural forms that are a response to a process of encoding a six-dimensional factor space, constructed from polar coordinates, time, material properties and solar climate. It does so by the application of matter properties to digital construction elements, which by successive application constructs building formations.

Chapter 10: Thermal Tectonics II

The chapter presents an idea and design method using dynamic input into a deterministic evolutionary computational method allowing the designer to modify the search target and thus approach a non-deterministic approach for environmental human-driven architectural design focused on thermal environmental aspects. It illustrates the method through the idea of organising brick assemblies, not only according to structural and expressive aspects, but also from a thermal environmental perspective. By applying the evolutionary model developed through design experimentation, a full-scale physical probe is suggested and constructed as a demonstrator of the approach. The proposed model and demonstrator are then evaluated and discussed in relation to potential further research inquiries.

Chapter 11: Thermal Tectonics III

It has been attempted in this chapter to construct an environmental tectonic probe on the basis of the above aspect and previous studies and conclusions. The design model is constructed of three interacting models: an environmental simulation model, an evolutionary model and a parametric model. The core investigation aims to explore the capacities for a multi-matter brick envelope and the effects of the matter organisation defining the perceived sensations. From this, the study presents the theory and methods of perceived thermal environments for humans and how these are applied into the specific evolution based design methodology. Following the description of the computational methods used and developed, a preliminary study is performed as an elementary setup to illustrate the method as a design approach. Based on this provisional example, a pavilion structure has been developed to construct a larger envelope with different climatic environmental orientations to test the ability to construct differentiated environmental formations across the envelope.

Chapter 12: Thermal Tectonics IV

In this chapter, the variables related to bi-material composites are investigated with the aim of understanding the interrelations of the material composite, the impact of thermal sensation experienced by humans through the workings of the responsive bi-materials, and the way these factors relate to a specific climatic environment. The intention of the inquiry is to move beyond the current architectural research of isolated material studies, into the interdisciplinary, architectural-engineering scale of material mechanics, environmental effects and human-related perceptions of temporal responsive architectural constructions. In the present study, time as a factor is explicitly integrated as the property and combined effect of each factor; materials, environments and humans are only understood over time. Hence, this study focuses on the interactions and relationships, which suggests a new instrumental approach to the integration of time-active elements. The research objective is pursued through the integration of a set of computationally simulated processes: simulation of bi-material behaviour, simulation of thermal sensation based on extended methods, with origins in Fanger's method of thermal comfort, and a simulation of an evolutionary process that correlates environmental dynamics, material dynamics and human behavioural and physiological dynamics.

Chapter 13: Thermal Tectonics V

The chapter presents bi-material studies of manipulation of assembly composite layers, thereby ‘programming’ the merged material effect desired towards modifying thermal environmental conditions. Copper and polypropylene are used as base materials for the composite structure due to their high differences in thermal expansion, surface emissivity alterations, their respective durability, copper’s architectural (visual and transformative) aesthetic qualities, as described in the chapter Tectonics, and their accessibility within the industry, making the study directly accessible to others, in contrast to studies based on highly limited and laboratory-based exclusive materials. The ’programming’ of the combined material is approached by altering the relationship (lengths) between the two material layers (metals and plastics with isotropic thermal properties) into a variable composite structure. The research presents the methods used and developed, the way in which the behavioural composites act and perform, and a large full-scale prototype as a demonstrator and experimental setup for post-construct analysis and evaluation of the design research.

Chapter 14: Synthesis

This chapter serves to synthesise the theoretical propositions in part 2, chapter 3 to 6, and the experimental design work and findings in part 3, chapter 7 to 13, with current associated strands in architecture and architectural research not discussed earlier in this thesis. Hence, the intent is to further elaborate upon and position the research, after the theory building and the experimental work, and to mark the research boundaries with greater intelligibility. By elaborating the boundaries drawn by the delineation in the thesis, a starting point for further studies beyond this research may become clearer. Finally, the chapter is used as an additional basis for the concluding remarks and the proposed thesis contributions in the following chapter.

Chapter 15. Conclusions

This chapter intends to present the concluding remarks of the thesis. It includes a revisit of the project beginnings by pointing back to the initial problems and the objective formulated in the thesis Introduction. The revisit is also the starting point of a short thesis summary, including the synthesis of the previous chapter. This in turn permits the final propositions for an Environmental Tectonic approach to be formulated based on the theoretical and experimental findings. With these framed, the research questions can be answered. Based on these sections, the formulations of the core research contributions are listed and a last brief conclusion is offered. Finally, as a last discussion, reflections on results and research methods and potential future studies are discussed.

1

Introduction

1.0 Preliminary

This chapter intends to construct the initial background for the research project and form a first delineation of thematic and instrumental approaches. As a starting point, a brief motivational note is included below. This serves to position and orient the research project against the four state-of-art approaches to environmentally sustainable architecture subsequently presented: *Passiv Haus, Zero-Energy Buildings, Free Running Buildings* and *Performance Oriented-Architecture*. The intent is not to convey an exhaustive analysis of the four approaches, but to point to ongoing research activities related to this work. In this process points of critique are raised that subsequently form the basis of indeterminate aspects and initiation of research questions. These questions then point to the general problem framing, problem statement and objective of the dissertation. Following the problem and objective framing, the theoretical background for *Environmental Tectonics* is outlined, enabling a formulation of the core research agenda. This delineates the work further into three principal state-of-art thematic fields investigated throughout the project, these being *Environmental Architecture, Tectonics in Architecture* and *Computational Architecture*. An initial outline of these architectural fields will then be conducted, enabling both a synthesis and provisions of relevant indeterminate aspects to be pursued. This then leads to the overall hypothesis and research question of the project.

1.1 Motivation

It is captivating to think that we as humans, like some other species, construct and mould environments for ourselves to individually and collectively form and extend our physical world through architectural creations. The act of creating architecture is evidently multifaceted and connected to numerous aspects, some of which are considered peripheral, from environmental psychology to material science. It should be mentioned from the beginning that this research is inherently interdisciplinary at its outset, not with the intention to reduce or simplify any individual field's scientific importance, but rather to integrate, overlay and cross-fertilise the methods, models and objectives into a potentially richer study for an environmentally sustainable architecture that addresses current problems, both general and specific, which will be defined at a later point in this chapter.

My interest in this work, and the background for the same — that is, the study and creation of buildings with an environmental focus — were sparked before I attended university. During secondary school I had the opportunity to design a house, making a full-scale physical prototype of the join between the roof and wall. Furthermore, an environmental assessment was conducted as the project was carried out within the school programme entitled 'architecture and energy'. Environmental aspects have always been a driving theme for all investigations. Throughout my architecture and engineering cross-disciplinary bachelor studies at Aalborg University, two architectural master-degree studies at Aalborg University and the International University of Cataluña, and a two-year research inquiry into microprocessor-mechanical-driven adaptive envelopes, these aspects were the common thread, even before the beginning of this PhD project at Aalborg University. These properties and relationships in architectural constructs continue to surprise and provoke as indeterminate conditions between architecture and environment remain, while new knowledge and methods are created, adopted and adapted. From this, the project work can be understood as an ongoing study of how we can construct methods, models and subsequent buildings in a reciprocal relationship with the natural and constructed environments for the betterment of the human environment and the natural environment alike. While being of a normative character, the thesis is also intended to be valued as a cohesive theoretical and instrumental framework.

Today, architecture faces high demands on minimising or even ‘producing’ energy and very defined boundaries for exact thermal comfort zones. Related to the former, the latest Assessment Report, number five (AR5), from the Intergovernmental Panel on Climate Change (IPCC) describes our impact as a species, stating that it is *‘very likely’* that humans are the cause of increasing global warming by green house gases (IPCC 2014). This leads to a series of intensified climate-based events, resulting in more extreme weather. This active participation in modifying something as large, complex and important as the atmosphere we live in has caused scientists to state that we have entered a new age, the ‘anthropocene era’ (Holmes 2009), in which humans have the power, even if unintended, to create massive, unprecedented changes. The fragility of our climatic environment is noticeable when only a few degrees’ modification, as predicted in AR5, has the capacity to radically modify the conditions for animal, plant and human activities and conditions for living. In this connection, the American polymath Herbert A. Simon wrote in his book, *The Science of the Artificial*,

> *The world we live in today is much more a man-made, or artificial, world than it is a natural world. Almost every element in our environment shows evidence of human artifice. The temperature in which we spend most of our lives is kept artificially at 20 degrees Celsius; the humidity is added to or taken from the air we breathe; and the impurities we inhale are largely produced (and filtered) by man. (Simon 1996:2)*

The built environment is believed to contribute 30 percent of the overall production of greenhouse gases (Klimakommisionen 2010), with some studies reaching a figure as high as almost 50 percent of the entire CO2 production (Government 2008) when including the associated activities that the building industry relies on to work. The impact of contemporary architectural production on our climate is massive.

Generalised thermal comfort principles are, to a large degree, the cause of the production of greenhouse gases and other human-influenced hostile environmental pollutants that arise from the use of fossil fuel energy sources. During the last century we have seen a dramatic change in what we demand of our built spaces, initially driven by formalistic ideas with a subsequent necessary increase in the technological development of thermal modifying devices to resolve the difference between the formal architectural style and the local climatic context. However, architectural elements for defining and conditioning spaces, such as the wall, roof, window, door, foundation and spatial organisation, were with the invention of mechanical air conditioning freed from their normal functions. This change decreased the need for their articulation in relation to the contextual conditions and allowed the development of what was referred to as an *International Style*. In the optimistic words of architect Le Corbusier, this architectural agenda permitted liberation and detachment from the environmental conditions in situ.

> *How, you ask, does air move…keep its temperature as it diffuses through the rooms, if it is forty degrees above or below zero outside? Reply, there are murs neutralisants (our invention) to stop the air at 18 degrees Celsius undergoing any external influence. These walls are envisaged in glass, stone, or missed forms, consisting of a double membrane with a space of a few centimeters between them.…a space that surrounds the building underneath, up the walls, over the roof terrace… In the narrow space between the membrane is blown scorching hot air, if in Moscow, iced air if in Dakar. Result, we control things that the surface of the interior membrane holds 18 degrees Celsius. And there you are! … The buildings of Russia, Paris, Suez or Buenos Aires, the steamer crossing the Equator, will be hermetically closed. In winter warmed, in summer cooled, which means that pure controlled air at 18 degrees Celsius circulated within forever. (Corbusier, 1930:64)*

The industrial production of new buildings and a new technological integration of machinery propelled architecture away from its local environment and secluded humans by way of hermetically sealed buildings. The western world followed this architectural agenda, initially sealing and integrating mechanical constructs into institutional buildings, then theatres, cinemas and shopping malls; lastly, these constructs absorbed residential buildings (Bhatia 2010) in a building agenda that much of the remaining world appears to have adopted as a contemporary and seemingly perpetual method of construction. The consequence has been a looping process of separating the human even more by, for instance, increasing the volume by depth of buildings facilitated by air conditioners and artificial lighting, eventually leading to humans being without natural light or fresh air for extended periods.

Furthermore, the mechanical apparatus allows for an immediate and very defined setting of a so-called needed thermal comfort, in which temperature and humidity are described by the *Psychrometric Chart*, developed by Willis Carrier (Battle 2003). Not only did this support the commercial value of the air conditioner and therefore its successful spreading into all forms of buildings, it also effected people's perception of environmental conditioning and the ability of specified regulation by architecture. From explicit settings, the air conditioner provides a given environment in which humans should experience thermal environmental comfort. By this approach, humans have been accustomed to ever-increasing possibilities of regulating their indoor environment by technical constructs [Fig. 1.1], which, not surprisingly, has been met with increasing technological machinery to accommodate those demands. In his provocative description of architecture, which is still valid today, American architectural theoretician Reyner Banham points to the centre of this development.

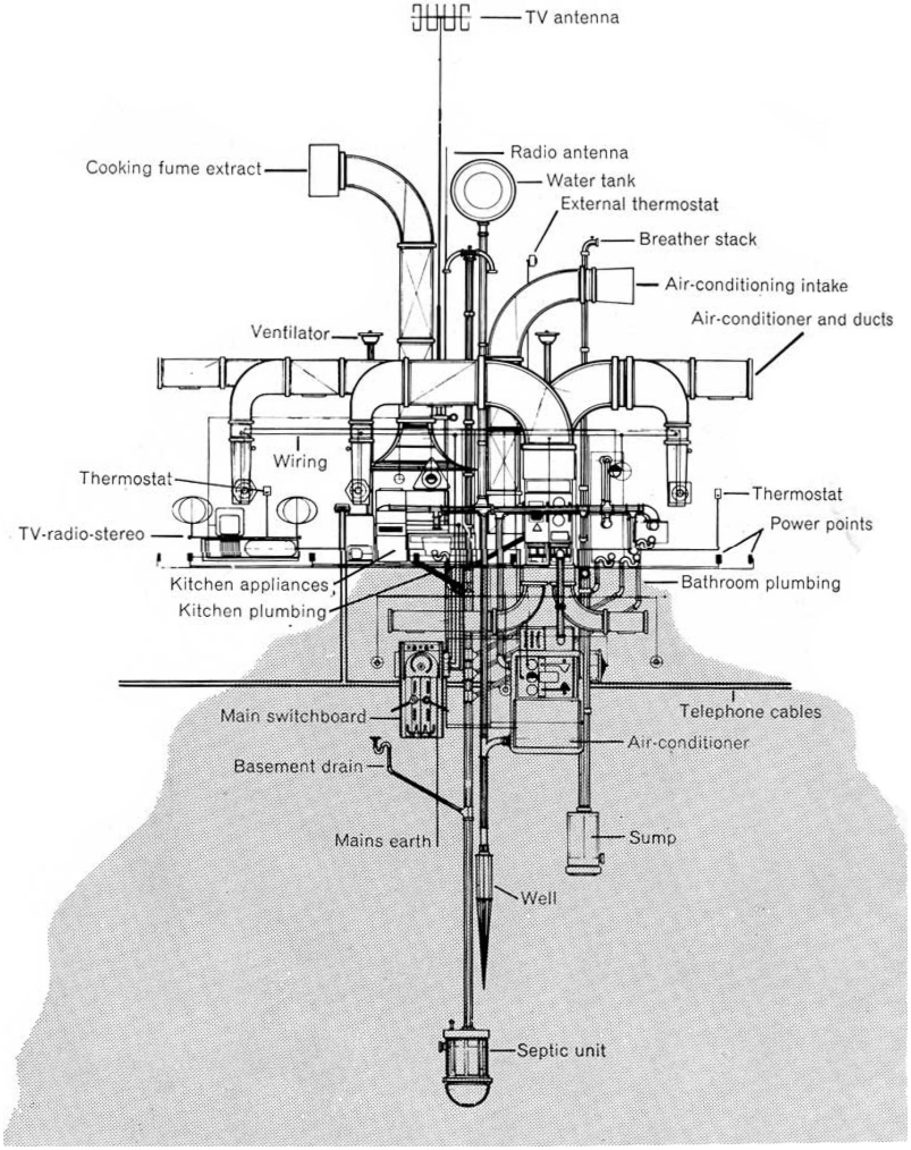


Figure 1.1

The building as a construct of technical machinery indicating the actual anatomy of a dwelling according to architectural theoretician Reyner Banham. Drawing by Francois Dallegret (1965)

> *For anyone who is prepared to foot the consequent bill for power consumed, it is now possible to live in almost any type or form of house one likes to name in any regions of the world that takes the fancy. Given this convenient climatic package one may live under low ceilings in the humid tropics, behind thin walls in the arctic and under uninsulated roofs in the desert. All precepts for climatic compensation through structure and form are rendered obsolete. (Banham, 1984:187)*

With the extensive technological development that has occurred since the 1980s, architecture relies heavily on mechanical constructs and an ever more refined measure of sealing the interior from the exterior. In Denmark, considered a highly developed country in relation to architecture, building techniques and technologies, demands of air-tightness of buildings lie at the fulcrum of building construction practice. Since 2008, a procedure of pressure tests of buildings, measuring their ability to eliminate environmental connectivity (Energistyrelsen 2014) and thus be more easily regulated by new machinery, appear to continue the approach initiated by the early air-conditioning strategies (Moe 2010).

Thus, architecture today entrusts large technological machinery with the performance of its most fundamental tasks of conditioning spaces for humans. This is the case even to the degree that architectural articulation, as Reyner Banham proposes, and as is shown in the Centre Pompidou [Fig. 1.2] by architects Renzo Piano and Richard Rogers, is the result of technical constructs with subsequent architectural expression and identity. While it is arguable whether the Centre Pompidou manifests this development as an articulated architecture with more profound intentions, putting into practice the theoretical notions of Banham, it is possibly not with the same rigour and intent that the predominant application of ventilation ducts, HVAC machinery and the like is applied to buildings in general.

1.2 Four Approaches

With a view to modifying architecture to meet a sustainable built environment, different building approaches over the last decades have been developed. Four significant directions, the Passiv Haus, Zero-Energy-Building, Free Running Buildings and Performance-Oriented Architecture approaches, are briefly described below, as they illustrate four different agendas to meet the aforementioned increasing demands in building codes initiated by the changing natural climate.

Passiv Haus

The Passiv Haus (PH) [Fig. 1.3] approach has been developed and predominantly integrated in the German-speaking countries and to some extent in Scandinavia due to the demanding governmental-initiated energy codes in these countries, and focuses on providing a rigid guideline with the intent of fulfilling an energy standard. As outlined

Figure 1.2

Centre Pompidou in Paris by Richard Rogers and Renzo Piano (1977) designed with its ventilation ducts, piping et cetera as the visual expression of the building. Photographer unknown.

by the Passiv Haus Institute (PassivHausInstitute 2014) to obtain the characterisation and Passiv Haus certificate, a building must follow a series of technical demands on construction principles and energy consumption. These demands are formulated as ‘space heating energy demands’, ‘primary energy demands’ and ‘airtightness’. Together with these energy-based demands, one comfort condition is prescribed. It states that for no more than 10% of the hours over a year must the indoor air temperature be over 25°C. Wolfgang Feist, the Passiv Haus concept co-author and founder of the Passiv Haus Institute, stated that:

> *A Passive House is a building in which thermal comfort [EN ISO 7730] can be guaranteed by post-heating or post- cooling the fresh-air mass flow required for a good indoor air quality. (Feist 2007)*

Feist asserted that the Passiv Haus’s intent is to construct good indoor air quality. By the principal guidelines provided, this has, in many cases, led to extremely insulated and sealed buildings, driven by an increasing move towards airtightness and energy recovery systems. This development has led to the progress of advanced technological components, such as windows and thermal bridge reduction in prefabricated elements and their implementation in thousands of buildings, as documented in the PH conference proceedings (PassivHaus 2014).

The success of the PH concept, with its own conference series initiated in 2006 (Passiv Haus 2006), can perhaps be explained by its relatively easy way of approaching sustainability-oriented architecture. The guidelines provide a short, clear list of four primary requirements that need to be considered by the architect and engineer. A building component database is accessible for the practitioner to further exemplify and help application of the concept. However, it can be argued that the approach, with its focus on isolation and energy efficiency, is based on the idea of saving energy, rather than an integral and systemic organisation of energy flows and the implementation of these as means for architectural production (Moe 2013). Also, despite the fact that the Passiv Haus concept makes use of solar energy to improve its energy balance, it can be argued that the PH concept lacks thermal environmental sensation descriptions because it does not integrate dynamic aspects in relation to the climatic environment and occupancy behaviour.

Zero Energy Buildings

Different yet similar approaches are developed by Zero Energy Buildings (ZEB) concepts, which in their description are more open to the different aspects of building design processes, given that they are defined by component, system and concept levels intended to define aspects from heat pumps via building service systems, to architectural aspects (Svendsen et al. 2014; Bejder et al. 2014; Brand et al. 2014). The most significant difference perhaps lies in the buildings ability to form into different configurations by being conceptually and practically organised in clusters and in ways in which energy is used and passed on to other ZEB buildings. Thus, the approach is

Figure 1.3

Velux Passiv Haus (2010) by Juri Troy Architects designed to follow the outlined requirements for the Austrian climate. Photo by Adam Mørk.

more open to architectural design aspects offering a series of design principles (Bejder et al. 2014) rather than solely stringent technical requirements, allowing architects and engineers to modify and influence their design based on these principles of energy-based design solutions.

While the ZEB approach offers a much more open and integrative approach to energy- and environment-oriented architecture in comparison to PH, the architectural design approach remains as general principles that are potentially applied via an Integrated Design Process (IDP) (Knudstrup 2004). While IDP allows a more diverse and integrative application than the Passiv Haus and ZEB approaches, it does not appear to have influenced these approaches to integrate methods and models in which the time-based environment and material complexity is inserted as the form-analytical, form-exploratory and form-finding driver towards novel environmental and potentially sustainable architectures.

Hence, while both approaches move towards a sustainable built environment, PH and ZEB are primarily concerned with the improvement of energy saving aspects and are largely adapted from a technical orientation towards architecture, in which it must be noted that they have shown capacities to significantly lower the costs of heating and cooling (Marszal et al. 2012; Bejder et al. 2014).

However, it is worth noting that:

(1) Studies of constructed PH houses also show problems with the internal environment of the buildings (Brunsgaard et al. 2011), indicating that the primary driver and focus on energy potentially results in decreased thermal and atmospheric quality for humans.

(2) Furthermore, the two prevailing approaches are similar in that they generally do not shift away from an energy-based technology, but instead towards a lower-energy-consuming technology (Hensel 2013a:139).

From this, we see from two important perspectives, the approaches above appear, firstly, to discard the spatial-material potential of architecture to create environments for humans. Secondly, despite promising reductions in energy use, they maintain the agenda of energy devices by the continued application of machinery. While it is recognised that these methods show promising results for decreasing energy use in buildings, and that interesting technical developments have been proposed and developed, such as energy- recovering systems, the aforementioned approaches differ distinctly from the orientation of this work specifically because they prescribe a set of specific technical components or design principles, with the main objective being to reduce energy costs towards a sustainable architecture by technological developments and constructs or predominantly aided by the same.

This thesis attempts instead, as laid out below in *Objectives*, to prescribe an environmentally oriented and open design framework whose locus is interlayered dynamic environmental and material properties enabled by design-based computational processes. This approach aims to articulate environmental conditions that enrich human activities.

Free Running Buildings

Another approach to environmental sustainable architecture is based on omitting mechanical technical means when assessing thermal conditions. This approach, entitled Free Running Buildings (FRB), is based on the understanding of thermal conditions for humans without the use of regulatory mechanisms, such as the HVAC system, outside the heating season. The temperature band for this season is defined by 10 to 30 degrees Celsius. By studying the thermal response by humans, following the general conventions of asking about the thermal comfort of humans in a given environment, Nicol and Humphrey have shown that there exists a linear relationship between the outside temperature variations and the internal comfort temperature variations (Nicol & Humphreys 2002). From this, they formulated the 'adaptive thermal method', which is a:

> *…behavioural approach, and rests on the observation that people in daily life are not passive in relation to their environment, but tend to make themselves comfortable, by making adjustments (adaptations) to their clothing, activity and posture, as well as their thermal environment. (Nicol & Pagliano 2007:708)*

This brings several interesting aspects to this thesis. Based on observations from various countries, it is shown that comfort temperatures, the deviation from the neutral set point, can be found to range from 20-30 degrees Celsius (Nicol & Humphreys 2002). Also, the comfort temperature is much more dynamic in FRB, allowing a dynamic understanding of what comfort is. This deviates from the two approaches above, which are based on a specific and generalised comfort temperature. Nevertheless, the FRB approach has been adopted by the European Preample of the European Energy Performance of Buildings Directive, stating:

> *(…) the displaying of officially recommended indoor temperatures, together with the actual measured temperature, should discourage misuse of heating, air-conditioning and ventilation systems. This should contribute to avoiding unnecessary use of energy and to safeguarding comfortable indoor climatic conditions (thermal comfort) in relation to outside temperatures. (ibid.)*

The FRB approach is therefore in conflict with the two prior approaches. With FRB, a direct relation to the external environment is important, which allows a much more active relation to the human occupant. Instead of a deep isolation principle paired with technical control systems, FRB acknowledges the active role of the occupant in changing clothes, opening and closing windows and to changing posture, modifying the volume-to-surface relationship and exposure to external energy, such as irradiance. It exists as an environmentally sustainable building discourse open to architectures with an explicit and integrated relation to its environmental context. In addition to improving the direct relation between human and occupant, it also appears to support the physiological acclimatization of the human body to its environmental context across the year cycle. The idea of FRB is not new and is practically embedded in many European countries' vernacular building fabric (Nicol & Humphreys 2002). In spite of this, current norms seem to follow the first two approaches when addressing sustainable architecture today. In many concerns, following the brief outline of the aim above, the work here builds on the idea of FRB. This approach has recently been partially adopted and discussed by the Performance-Oriented Architecture approach, which is discussed below.

Performance-Oriented Architecture

Performance-Oriented Architecture (POA), as principally authored by the German architectural scholar Michael Hensel, is based on the continuation of the writings on 'performance' by American architectural theoretician David Leatherbarrrow (Hensel 2013a:28). In Hensel's work the focal point is the dynamic relationship between material organisation, environment, subject and spatial organisation (Hensel 2011:8). In this complex Hensel examines and positions performance beyond a mere functional agenda, following an elaboration of the notion of performance as related to 'events' and 'active agency'. Here, he inserts a more integrative architectural position in relation to a performative architectural approach. While also utilising the organisational diagram as a communicative technique, as is done within the ZEB design principles, Hensel prescribes the factors and aspects at work, such as material dynamics, rather than concrete design principles. These are then illustrated in specified architectural design proposals, such as the auxiliary architectural models and bending wood models (Hensel 2013b; Hensel et al. 2012). Inherent in the framework lie the processes of feedback between different aspects, or, again, agencies, which others adopting and adapting a performance-oriented architectural approach adhere to as a central aspect in theoretical branches, such as performance-based architecture (A. Malkawi 2005; Kolarevic & Malkawi 2005; Kolarevic 2005; Luebkeman 2003; Grobman et al. 2010), and in general performance-based design (Oxman 2008). As is evident in Hensel's and related researchers' work, several strands exist to further construct a performance-oriented architectural approach in addressing a broad set of architectural problems. The approach is overarching as an architectural orientation, while theoretically specified regarding the construct of microclimates and concepts of sustainability. Thus, Performance-Oriented Architecture is additionally often applied to architectural concerns with specified structural objectives (Pugnale 2009; Whitehead 2003a; Hensel & Bover 2013; Luebkeman & Shea 2005) or even programmatic objectives (Derix 2010). What makes performance-oriented architecture particularly engaging, in relation to this work, is its focus on dynamic capacities and local specificity, rather than on architecture under static conditions. This pushes the approach as an architectural theory beyond the idea of architecture as a static object, or what it 'is', to what it 'does'.

In effect, the work here points to several of the ideas in Free Running Buildings and Performance-Oriented Architecture, which will become evident throughout the thesis. The theoretical foundation of performance-oriented architecture examines closely what and how dynamics are present in biological, ecological and climatic systems and their possible implementation in the built environment. However, by addressing architecture through the above systems, it promotes also a somewhat non-anthropocentric architectural approach (Hensel, 2013b:45). Thus, it may to a lesser degree focus on how and examine why we as human beings, besides and beyond physiological stipulations, could be interested in an environmental responsive architecture that points towards environmentally sustainable architecture.

1.3 Problem framing and statement

While the aforementioned different architectural approaches pursue a sustainable agenda, with acknowledged advances in limiting energy consumption, the current general approach for building, and environmental construction in particular, is arguably on a path of increasing adoption and implementation of technical machinery. This then compensates for the deficiency of architecture to engage in direct environmentally constructed conditions for humans. This problem framing serves as the basis for formulating the problem statement of the thesis below.

A first obvious problem of a technical-oriented approach in architecture is that our technical constructs are almost solely made, maintained and driven by processes and means that are damaging to the natural environment. This problem has to do with diminishing resources through the extensive use of metals and fossil fuels and with the use and burning of energy sources that cause the release of greenhouse gases, negatively influencing the environment and reinforcing the development of new machinery in a cyclical manner, which increases the problem as a whole.

A second problem is the exceeding withdrawal of humans from their local climatic context, promoted by the tendency of architects and engineers to apply ever more technical devices. This being understood as a problem is perhaps less obvious, as can be understood by the enthusiasm of the International Style, as stated above, which is largely practiced today, though through formal expressions other than those used by the early Modernists. This problem is also described at the outset to define Performance-Oriented Architecture. Earlier research shows that the seclusion of buildings and humans has a direct impact on the psychological and physiological well-being of humans (Ulrich 1984; Fich 2014), traced directly to the health of people, and indirectly to the cultural identity, diversity and rooting of humans in space and time (Berthold-Bond 1994: 294; Hartoonian 1994:5).

A third problem is the lifetime or longevity of buildings. The longer a building is in use, the lower the initial economic and energy-related costs of construction. With the increasing integration of technical aggregates, with an expected lifetime of 20-30 years, architectures have an increasing need for exorbitant re-building of technical parts, which are costly from an economic and energy-related perspective.

A fourth problem is our static constructions in our dynamic environments. In relation to energy, recent research has shown that the future energy frames for buildings (Denmark) cannot be met by behavioural static constructions (Winther et al. 2009). Considering this problem from an architectural perspective, architectural critic Michael Speaks states that it is inherently odd that buildings are fixed constructions in a dynamic and diverse environment (Speaks 1998).

A fifth problem is the reduced capacity for methodological adaptation. This may seem redundant following the above problem statement, but is to be understood not as the adaptation of a singular architecture to its context over its lifetime, but as an applied architectural methodology that exhibits adaptive properties with different architectural projects. Here, adaptation lies in the capacity of the applied architectural methodology to meet a local environment, rather than the adaptive ability of a style or expressive ideology. For even if an architectural style is related to a 'foreign' context, it remains bound by a formal style born in another setting, effectively defying local specificity.

From an outline of the four most currently relevant approaches to environmentally sustainable architecture, a set of critical points has been framed. This context as basis for this thesis, and its inherent problem statement, are grounded in the notion that:

Architectural practice is on a path towards the isolation of humans aided by the technical constructs (as seen in PH and ZEB). And the environmentally open approaches either focus on human adaptation (as seen in FRB), rather than entrusting architecture to construct environments for humans, or focuses on performance architectures (as seen in POA), which do not centre the human as a measure for architectural articulation.

1.4 Initiating questions

The above approaches, problem framing and problem statement are used to formulate an initial set of questions that allow a first delineation of the research into paths of inquiry by asking:

How can environmental constructions enrich human-perceived environments? (Q1)

Performance-oriented architecture is theoretically rooted in theories of performance, from which the framework steers away from the formulation of an instrumental structure for human-oriented environmental construction models. While this allows the approach to be very open and method-based in character, supporting a wide range of specific design research investigations, as shown by its authors, it may also lessen its potential to unfold in other ways by omitting more explicit provisions for environmental form development. This presents the second question:

What is the basis for an architecturally elaborated construction model and how can it be formulated and made instrumental for environmental architectures? (Q2)

Most environmental assessment techniques that have been applied to Performance-Oriented Architectures, and IDP in general, have been developed for other purposes than for architectural development. While this allows a rigorous and tested analysis tool to be applied, it may also inhibit the architectural potential in that environmental assessment is confined to aspects desired within the fields from which the techniques have been adopted (Turrin 2014). This presents a third question:

(Q3) *What theoretical and instrumental assessment and environmental open-development models are needed to evaluate and evolve an environmental architecture?*

These initiating research questions guide the structure and investigations conducted throughout this dissertation. They serve, additionally, as a platform and point of reference to formulate the overarching hypothesis and research question presented in the end of this introductory chapter.

1.5 Theoretical Platform

The aforementioned problems motivate and position the research project and serve to construct the initial platform of knowledge fields by the questions asked. In addressing the problems and funnelling the span into a specific and feasible architectural research project, three core fields of architectural research are distilled throughout the project: Environmental architecture, Tectonics in architecture and Computational architecture. These fields are chosen based on the three initiating research questions above, probing a theoretical examination of the individual and over layered fields towards meeting the objectives of the project.

Inclusion of three fields, rather than solely concentrating on one field is moreover supported by previous research work with dynamic environmental constructed models in architecture (Foged & Poulsen 2010; Foged et al. 2010). The realisation that such models can only be described, constructed, explored and understood if they are influenced from environmental and tectonic aspects enabled by a form of computation, ask for the integration and potential development of theories within and across each field.

In an attempt to further exemplify the necessity of all three fields to be included and for further investigation throughout the project, the fundamental aspects of an architectural environmental adaptive system [Fig. 1.4] developed previous to this thesis project can be reassessed. The architectural adaptive model is based on four defined systems (Foged et al. 2010).

Material System
It is the physical construct of the adaptive system, including the geometrical organisation of elements and its dynamic geometric behaviour - joints, proportions, rotation, displacement, re-compositioning, et cetera and the material behavioural properties - elasticity, expansion, durability, conductivity, et cetera.

Processing System
It is the physical construct, often a microprocessor unit, of the adaptive system's ability to process information and compute decision making based on input from sensors, sending information as output for actuation in the material system. This

typically constitutes a feedback process between the constructed material system and the environment.

Informational System

It is the physical construct of the adaptive system's method of transferring information from the processing system, to the material system, to the environment and back, by, for instance, electric current, chemical signalling, light transmission or mechanical actions. The informational system is physical, but not necessarily visible.

Behavioural System

It is the metaphysical construct of the adaptive system with the ability to compute behavioural actions based on both its sensing of the environment and its utilisation of memory (database) information. The behavioural system is typically encoded with algorithms that are able to modify behaviour in order to transcend its regulation from a responsive to an adaptive behaviour.

The withdrawal of the material system results in a non-physical adaptive system functioning only in theory, not in the built context of architecture. Furthermore, it is not possible to define the conditions and physical boundaries embedded into the behavioural system if there exists no physical definition of the problem/solution space to operate within. If we extract the behavioural system, the model as a whole is left without any means of responding to sensorial input or suggesting output for actuation within the material system. If the processing system is removed, where does one situate the behavioural system that is necessary for adaptive properties? And, if omitting an information system, the material system, behavioural system and processing system might work separately, but not as a whole.

Informational signalling might be of a chemical character. The same goes for processing the information, as is evident in biological systems (Heylighen 2008). This means that a processing system and information system could be merged with the material system as one entity, in contrast to the adaptive model used here, for example, where all four systems are intrinsically visually and operationally divided. The concatenation of three systems into one does not, however, abandon the individual properties of each system and its unique definitions.

Hence, to neglect the ability of a construct to interact with its environment, including humans, reduces architecture to a non-responsive entity disconnected from its context. If the articulation of the construction is excluded, submitting to theoretical architectural models alone, the architecture's physical dimension remains unresolved. And if we omit computation, in its broadest sense, architectural construction reduces its capacity to change environmental and human conditions into environmentally sustainable architecture for humans.

Adaptive Model by Foged et al. (2011) illustrating the informational system, the material system and the processing system with an embedded homeostatic based adaptive algorithm. Photo by Isak Worre Foged.

1.6 Objective

As a consequence of the aforementioned initial problems, preliminary notions and initiating questions, the objective of the research project is twofold. The thesis attempts to contribute to architectural theory and its orientation towards a human-oriented environmental sustainable approach, and to identify, exemplify, explore and propose specific instrumental design methods and models within this theoretical position.

On a theoretical level, the objective is to identify and formulate a theoretical and methodological framework for such an approach. The intended framework is based upon a series of prescriptive propositions, rather than taking the form of a guide or design principles. This has the intent of creating an open and expectantly adaptive theoretical model for both an approach to the existing sustainable architecture orientation and a contribution to what is considered a tectonic architecture orientation. This is a response to the current tendencies and associated problems.

On an applied level, the objective is to formulate and develop a series of specific methods and models that test and demonstrate potential specific approaches to reach what is theoretically formulated as Environmental Tectonics. These models are considered both demonstrators and experimental probes at the same time.

Inversely, the objective of the thesis is not to restrain or automatise the creative and often elusive architectural design process. Instead, it attempts to support, on both theoretical and applied levels, the development of methods and models based on a broad yet human-oriented approach to environmentally sustainable architecture. It does, however, recognise that the architectural theorist and practitioners must work in an interdisciplinary manner, with knowledge within the three core fields forming the basis for this work.

While the theoretical propositions are located in Fields (part 2) and the instrumental methods and models in Probes (part 3), these research activities cannot be considered separately. The theories and ideas presented in part 2 are, more often than not, a product of examinations conducted in part 3 and vice versa.

1.7 Three Fields

In order to further delineate the orientation of the thesis, the three fields of Environmental Architecture, Tectonics in Architecture and Computational Architecture are addressed throughout the work in relation to the initial architectural design conception, the conceptual phase of design and the early development of architectural constructs (Lawson 2006; Cross 2002).

The reason for this is that, firstly, the quality, final effect and affect on humans and environments as an environmental sustainable architecture is largely created in the early phase of design development (Turrin 2014; IEA 2009), thus substantially increasing the final positive impact on architectural projects as a whole. This, however, does not suggest that the subsequent design and construction phases can be ignored or otherwise reduced as a whole. Secondly, by focusing on early architectural design methods and models, the integration of environmental aspects as drivers of design

Greater London Assembly (2002) by Foster and Partners with the central space forming the assembly further below, which was acoustically optimized in accordance with the sound spreading by the politicians. Photograher unknown.

development, rather than as post-design analysis procedures, is asserted to empower the architectural designer in a building industry with many agendas other than the environmental.

Within each of the three architectural fields, Environmental Architecture, Tectonics in Architecture and Computational Architecture, there exist notions of state-of-the-art work. However, these positions are often indistinct and potentially contrasting in their theoretical definitions. Additionally, research work in Tectonics in Architecture is discussed on a predominantly theoretical level, while Computational Architecture is investigated on both a theoretical and an applied level. Pointing to definitive current research summits in each field is therefore difficult, due to the scattered research agendas and theoretical formulations. Nevertheless, the following section seeks to suggest and present a state of research in which a minimum of two of the three fields have been interweaved. This section's intent is to map the current research work related to this work, position the thesis within environmental sustainable architecture and inform the formulation of the overarching hypotheses. This then becomes the basis for building the theory in the next chapters by returning to each of the three fields with an emphasis on the theoretical foundation of Environmental Tectonics in architecture.

Environmental Architecture

It is an assumption of this thesis that environmental architecture is essentially sustainable architecture. If architecture does not mediate between a desired environment and a climatic host environment, it enforces, as briefly mentioned above and in referenced research work, financial, atmospheric and energy costs to improve the environmental creation to meet conditions for humans. Conversely, if architecture engages between the environment and humans, these energy-related problems may be diminishable. For this reason, the study of environmental architecture is framed by environment-oriented architecture investigating environmental capacities in a move towards sustainable architecture. In particular, two forms of environmental aspects in architecture are addressed in this thesis, the acoustic environment and the thermal environment. This orientation aligns with the European Standard, EN15251, definition of what aspects are important in determining the indoor environment, stating: '*Indoor environmental input parameters for design and assessment of energy performance of buildings – addressing indoor air quality, thermal environment, lighting and acoustic*' (Olesen 2012). The thermal environment is directly linked to the thermal sensations and perceptions of human thermal comfort underpinning the path towards a sustainable architecture, whereas acoustics are connected to environmental architecture through its impact on human spatial comfort and the conception of architecture as a whole (Hosey 2012; Rasmussen 1964; Zumthor 2012).

Acoustic

Forming architectural environments based on acoustic aspects is typically reserved for concert halls, auditoriums and large music studios. In the Greater London Assembly building (2002)[Fig. 1.5], the architectural office of Foster and Partners + ARUP engineers have shown one of the most convincing built projects illustrating the combination of acoustic simulation and architectural creation by digital parametric modelling. The assembly hall's internal space is parametrically modelled and can be analysed in response to acoustic parameters. Iterations between modelling of the space and analysis of the sonic environment gradually advance the design development towards a specific acoustic property suited for the audible purpose of the local political governance (Whitehead 2003b; Kolarevic 2005).

While the above architectural design procedure iterates between the analytical and modelling activities, Sato et al. have shown a model in which acoustic simulation of reverberation time is directly paired with a computational optimisation algorithm by modifying the overall spatial geometry in large triangular planes determining the geometry of a concert hall towards a specified acoustic target (Sato et al. 2004). Similar studies of the modification of large spatial geometries by a computational search algorithm have been shown in the transformation of an existing concert hall by Spaeth and Menges (Spaeth & Menges 2011) and in another concert hall studies by Pugnale (Pugnale 2009) and Echenagucia (Echenagucia 2014). The studies bear much resemblance to the work carried out by Sato, but they implement more visual design control as determined by the design parameters that can be included for design progression. Another study of a concert hall, applying an agent-based algorithm, was explored by Lim, with a particular focus on the considerable sound-reflectivity of the roof to improve the distribution of sound across a deep space (Lim 2011) in which a digitally modelled ceiling changed curvature as a way to physically modify the expression and properties of the sound-reflecting ceiling.

On a different scale, Peters et al have explored the architectural model as related to acoustic properties, with a specific focus on the effect of patterning surfaces to induce specified sound scattering (Peters & Olesen 2010). Contrary to Sato et al, who studied the overall geometry of the space, Peters is focusing on a wall segment's acoustic properties by predetermined design patterns. In a later study, Peters et al construct a full-scale wall segment, exploring similar effects of scattering but with the intention of directing the sound towards a singular point and shielding of another zone with the same wall. The procedure between analysis and modelling is iterative but not coupled as a looping design system (Peters et al. 2011).

Recent architectural acoustic studies related to the early design phases appear to be approached on two different scales: the large concert hall scale, predominantly focused on geometry, computational parametric models and potential links between analysis and visual models with modification by search algorithms, and small-scale physical studies of components of singular wall segments towards surface articulations by segregated analysis and modelling activities.

Thermal

The application of thermal aspects in architectural research has predominantly been incorporated as an engineering methodology in design through the use of highly specified and expertly calculated (Ericsson et al. 2007) physical measurements and computational analysis methods. In studies where thermal analysis has been coupled with computational search methods, analysis has moved from a post-design application to a design activity lending itself to modes of design synthesis as well as numerical assessment. From the combination of pairing analysis with partially automated modelling, the process becomes an early design phase activity, designated by architectural researcher Ali Malkawi as aforementioned Performance-Based Design (A. M. Malkawi 2005; Malkawi et al. 2005). However, the studies by Malkawi et al are predominantly architecturally schematic in character, as they define a simple rectangular geometry with openings defined as windows, doors and ventilation inlets/outlets. The design model then iterates between a commercially available Computational Fluid Dynamics (CFD) solver that analyse the thermal flow, an open library evolutionary search algorithm and a geometric output visible to the designer. While advanced in its computational setup, the architectural solution space remains somewhat restricted by the initial simplified geometrical input as an architectural representation and by the mode of environmental assessment. In an analogous approach to design studies and theoretical work by Malkawi, Luisa Caldas et al (Caldas, Norford, & Rocha, 2003; Caldas, 2006, 2008) have performed similar studies by modifying an existing building design with a goal of improved energy scores. This is done by coupling the engineering oriented DOE2.1E energy simulation engine with different types of evolutionary algorithms. These studies apply more comprehensive architectural models, but remain largely focussed on the optimisation of a pre-set geometry towards the optimisation of building code energy scores. Recently, Tomas Mendez have shown similar energy based parametric search models (Echenagucia 2014) and David Gerber et al (Gerber & Lin 2012; Gerber et al. 2013) have worked on more diverse geometric forms than the previous studies by Malkawi, Caldas and Mendez to bring the approach to architectural design problems closer to practice by coupling multi-objective evolutionary algorithms (MOEA) with an energy simulation engine, with the aim of improving energy balances and financial scores. The work is focused not only on the development of an architectural method, but also on the testing of this model in a student design situation, where architectural graduate students attempt to design via this approach.

Previous research work in this field, that is, the combination of environmental assessment and computational form finding, is still in its infancy and thus very limited in quantity and diversity. Furthermore, the above references lie somewhat outside the scope of intention of this work, as they focus on bottom line building code energy scores, rather than the construction of specific thermal environments that subsequently may improve energy balances. It seeks to support the notion that the preliminary questioning of a performance-based architecture remain specifically interested and directed to fulfill established energy codes by engineering-oriented technologies, rather than to explore and formulate architectural agendas for the built environment that are by necessity local specific.

Ironically, engineers, who use and develop the methods and models for assessment, have recognised problems with this form of general oriented assessment by teaming up with sociologists. Although advanced and comprehensive in the implementation of different aspects, the current energy models do not allow sufficient integration of the material and environmental dynamics and behavioural properties of humans (Gram-Hanssen 2010; Gram-Hanssen 2011; Gram-Hanssen 2014).

Furthermore, when focusing on thermal aspects in the early design phase, previous studies are commonly framed by what Malkawi terms 'single domain tools' (Malkawi, 2005:87), which are single oriented factor studies, such as analysing daylight levels, as can be seen in many studies (Biloria & Sumini 2009; Pasold & Foged 2010; Foged & Poulsen 2010; Hensel 2010), or the flow of air to develop the external design profile of a building or internal space organisation and openings towards a solution from a particular ventilation strategy (Chang 2013; Menicovich et al. 2012; Moya et al. 2013; Moya et al. 2014).

When these studies become related to acoustic and thermal aspects as drivers for early design development, they illustrate a research approach to architecture that takes the audible and thermal as a point of departure and centres the relationship between the human perceiver and environment in the foreground of architectural making.

Current architectural research studies, which provoke design development from environmental aspects, appear, however, to be oriented towards singular factors, such as improving the exposure to daylight of a given space and the flow of air around or inside an architectural form. The measure of daylight in an architectural space is undoubtedly a central aspect to consider. But as it impacts more than our visual understanding, one may discuss a broader impact and understanding of the climate-based environment, its factors and how one can make it instrumental in the conception of architecture. Also, following from the initial questions, one may discuss how architectural instrumental models can be formulated and activated in combination with environmental constructions in general.

From this we can discuss the following as an extension of the previous questions:

(Q4) *How can analytical and numerical methods of human sensations of the environment be integrated into the architectural conceptual design phase?*

And:

(Q5) *How can the relation between a structure and an environment be understood for environmental constructions?*

Tectonics in Architecture

In her book, *Tectonic Visions in Architecture*, Danish architectural scholar Anne Beim (Beim 2004) elaborates on concepts and orientations classified as tectonic projects. She describes a field of approaches to building that suggest what Tectonics in Architecture are. Her work follows a tradition, which is discussed in the chapter on Tectonics (chapter 4), describing tectonics in terms of built architectures. The development of tectonics as an orientation in academia beyond a theoretical direction appears to be a more recent endeavour. In keeping with the aforementioned method of looking at two of three fields central to this work, research work is outlined below that is focused on the combination of tectonics and computation, or what recently has been formulated as Digital Tectonics (Liu & Lim 2006; Andersson & Kirkegaard 2006) with theoretical branching into Digital Tectonic Generation and Digital Tectonic Fabrication paths (Kolarevic, 2003; Liu & Lim, 2006:303).

Digital Tectonics

Digital Tectonics is concerned with the notion of digital making as the immaterial counterpart to the tectonic, which is material-bound (Liu & Lim 2006), and thus discusses the theoretical relationship, oppositions and potentials of combinations between these architectural orientations. Specifically, it is concerned with the *'renewed interest in structure…facilitated by the use of digital technologies'* (Leach et al. 2004). In this manner, it both deviates from, while at the same time following, the classic academic tectonics in architectural approaches through evaluation of built and sometimes un-built projects, with the objective of establishing the path as a theoretical position beyond its classification as a technical tooling appendix to classic tectonic thinking.

Digital Tectonic Generation

Generation, as related to Digital Tectonics, is oriented towards integrating methods of structural simulation and digital generation of form, allowing new forms to be developed based upon the material properties and structural force scenario processed by geometric calculations. Axel Kilian has shown several models of such a capacity (Kilian 2006) with a particular impact on funicular and spring models, followed, among others, by the research works of Sean Alhquist on textile spring models (Alhquist & Menges 2013), Phillippe Block and Matthias Rippmann on funicular models and the development of graphical statics as a basis for form-finding (Rippmann & Block 2013; Mele & Rippmann 2012)[Fig. 1.6], and Paul Nicholas on spring and fibre composite models (Nicholas 2008; Nicholas & Tamke 2012). Of more general application is the extensive work on computational geometric methods, an approach that has been advanced by Daniel Piker (Piker 2013) and Bollinger, Grobman and Preisinger (Preisinger & Heimrath 2014; Preisinger 2013). Form-finding is created from a predefined geometry that undergoes changes after forces are applied through computational simulations. In this respect, it follows its analogue predecessors, such as the catenary chain, as described by Hooke's principle (Hahn 2012) and, from that, the early models of architectural explorations by the Spanish architect Antoni Y Gaudi (Burry 2006), the German architect and engineer Frei Otto (Otto & Rasch 1996),

Figure 1.6

Catenary structure in Barcelona by Studio Map21 (2014) based on the RhinoVault form-finding software developed by Matthias Rippmann et al. Photo by Manuel de Lozar and Paula Lopez Barba.

and the Danish engineer Erik Reitzel (Reitzel 1975), to mention the most prominent contributors of this method.

Digital Tectonic Fabrication

Fabrication as related to Digital Tectonics focuses largely on new fabrication methods exemplified by experimental casting techniques, often after a Digital Generation procedure, such as topology-optimisation procedures (Søndergaard et al. 2013). Here, a structure is created from the process of withdrawing and repositioning material until a given load condition is met. Potentially better-known applications of computer numerical controlled (CNC) fabrication techniques and computer numerical controlled assembly techniques are seen in the work of architects and researchers Gramazio and Kohler (Bonwetsch et al. 2007; Gramazio & Kohler 2008; Gramazio & Kohler 2010). Gramazio and Kohler have predominantly explored the capacities of robotic manufacturing from a conceptual architectural design perspective. Their work is aimed at making and controlling a digital fabrication output by way of an explicitly defined formalistic design input. These studies are continuously being technologically expanded by the authors with the robotic manufacturing methods. Parallel to this, advanced CNC processes have been integrated into other architectural projects by Johannes Braumann and Sigrid Brell-Cokcan, founders of the *Robots in Architecture Association* (Braumann & Brell-Cokcan 2012), with extensive applications in research projects being undertaken by, among others, Achim Menges and Jan Knippers et al (Menges & Knippers 2015), focusing on advanced fabrication methods through the use of robotics.

As mentioned before, both Digital Generation and Digital Fabrication are, in the above examples, rooted in the conceptual phase of design and oriented towards an exploratory mode of work. In addition, both approaches are oriented towards the exploration and optimisation of constructions primarily in relation to structural objectives and the advancement of the manufacture of these structures. Hence, tectonics, while oriented towards structural issues in Digital Tectonics, is currently elusively defined, particularly in relation to environmental aspects, which underpins the necessity for a theoretical study and framework of Environmental Tectonics by a visit to the underlying notions of tectonics.

Hence, we can also discuss, in addition to the initial questions:

How can tectonics be oriented towards and become instrumental for an approach to environmentally sustainable architecture? (Q6)

And from here, we can also consider:

What modes of architectural instrumentation are applicable to support this orientation? (Q7)

Computational Architecture

The integration of digital techniques and technologies into architectural research has, over recent decades, expanded the field of inquiry substantially (Kolarevic 2003a; Kolarevic & Malkawi 2005; Oxman 2006; Oxman 2008; Oxman & Oxman 2014) with increased branching through the adoption of computational methods from the fields of computer science and engineering science. The largest international conference for computation-based architectures accepted 27 different topics for submitting research work into its 2014 edition, from Digital Heritage to Generative Design (eCAADe 2014).

Following the objective of this thesis, two orientations of computation become particularly relevant: the ability to understand and create environmental architectural forms, by generative, or developmental processes, and evaluating environmental architectural forms, by simulated assessment processes.

Computational Simulation

Digital simulation processes in science are based on mathematical models, which, again, are based on physical measurements that have been generalised so as to be applied to different inquiries across different scientific fields (Winsberg 2001; Winsberg 2010). Simulation in architecture is extrinsically linked to other knowledge fields in which the simulation methods have been developed, such as structural, acoustic and climate engineering. This means that a form of scientific and technological adoption must take place either by bridging different architectural models and engineering models or by expanding the architectural models with integrated simulation modules by direct application of the underlying mathematical models. In either case, substantial knowledge of the utilised adopted theory must be absorbed in order to understand and construct meaningful architectural investigations. Adoption and adaptation of simulation methods from other fields into architectural methods and models become central to this thesis when focusing on the early design conception. Furthermore, simulation speed becomes important in allowing fast feedback to reach the architect, in order to make decisions based on the information gained from the simulation. In relation to environmental simulation, researchers have focused on bridging architectural digital box models (simple rectangular geometries) to established thermal simulation software, as can be seen in the multiple studies by Luisa Caldas et al and Ali Malkawi et al (Caldas 2008; Malkawi et al. 2005).

While some structural principles, such as Hooke's Law as a mathematical basis of the aforementioned catenary models, are possible to readily integrate into architectural models, thermal analysis by simulation poses another challenge from the numerous interrelated physical aspects that need to be understood and integrated. The primary challenges appear to be a fast feedback and versatile design input and output procedure, the reason being that conceptual design relies on a rapid iterative working mode (Akin & Lin 1995). One aspect within the field of thermal assessment is Computer Fluid Dynamics (CFD), computing the flow of a fluid in a defined space.

Even by contemporary computational power, these simulations at the building scale are complex and computer processing is costly, resulting in unfeasible timespans for conceptual design work. This makes these simulations less viable to integrate into early architectural methods and models. In approaching this problem of speed and immediate feedback, researchers have worked on simulation models, which render an image of what the fluid flow could look like, but are not physically accurate (Stam 2003; Attar et al. 2009; Stam 2009). However, the environmental aspect of CFD is gaining increased research attention as it connects to the understanding and exploration of several other aspects related to environmental control in architecture, from air conditioning systems to urban flooding models. It remains, nevertheless, in its infancy when it comes to application to early architectural design models.

Another series of environmental simulation aspects, related directly to the sun – sunlight, daylight and irradiance – has recently been integrated through parametric modelling into digital architectural models by linking engineering software, such as EnergyPlus and Radiance, with the ability to simulate the amount of sunlight, daylight, received solar energy and energy use. While the latter is based on geometric properties between the Earth and the sun, the former introduces further advanced properties by adding the material properties of a construction to calculate, among other factors, the transmission loss of energy. By adding a substantial complexity to the physical assessment of the building's boundary layers, it substantially influences the description of the thermal environmental conditions. Architectural models based on solar aspects have recently been explored as a basis for architectural assessment in architectural practice (Banke 2013) and as studies of simulation techniques in architecture (Sharaidin et al. 2012).

To maintain the focus of an architectural approach to Environmental Tectonics and the integration of environmental simulation during the making of this thesis, the real time calculations of fluid flow are omitted; however, they are integrated as a parameter in the evaluation of thermal sensations and thermal comfort.

Where it is meaningful in relation to the objective, the work here utilises prior research-enabled computational modules, whereas in the cases of non-existent prior work, new computational simulation modules are created and integrated directly through programming as part of the developed architectural models. These efforts are explained in more detail during each design research experiment in Probes (part 3).

Computational Generation

With the expansion of computational techniques and the development of programming languages that are oriented towards creative processes, architectural form creation has become an attainable and a distinct approach to conceptual architectural processes (Riiber 2013). From this orientation, multiple techniques of form-generating processes are developed and explored in architecture. Significant attention in relation to the development of this thesis has been given to *Agent-based systems*, *Shape Grammar systems*, *Fractal systems* and *Evolutionary systems* for reasons that will be elaborated upon below.

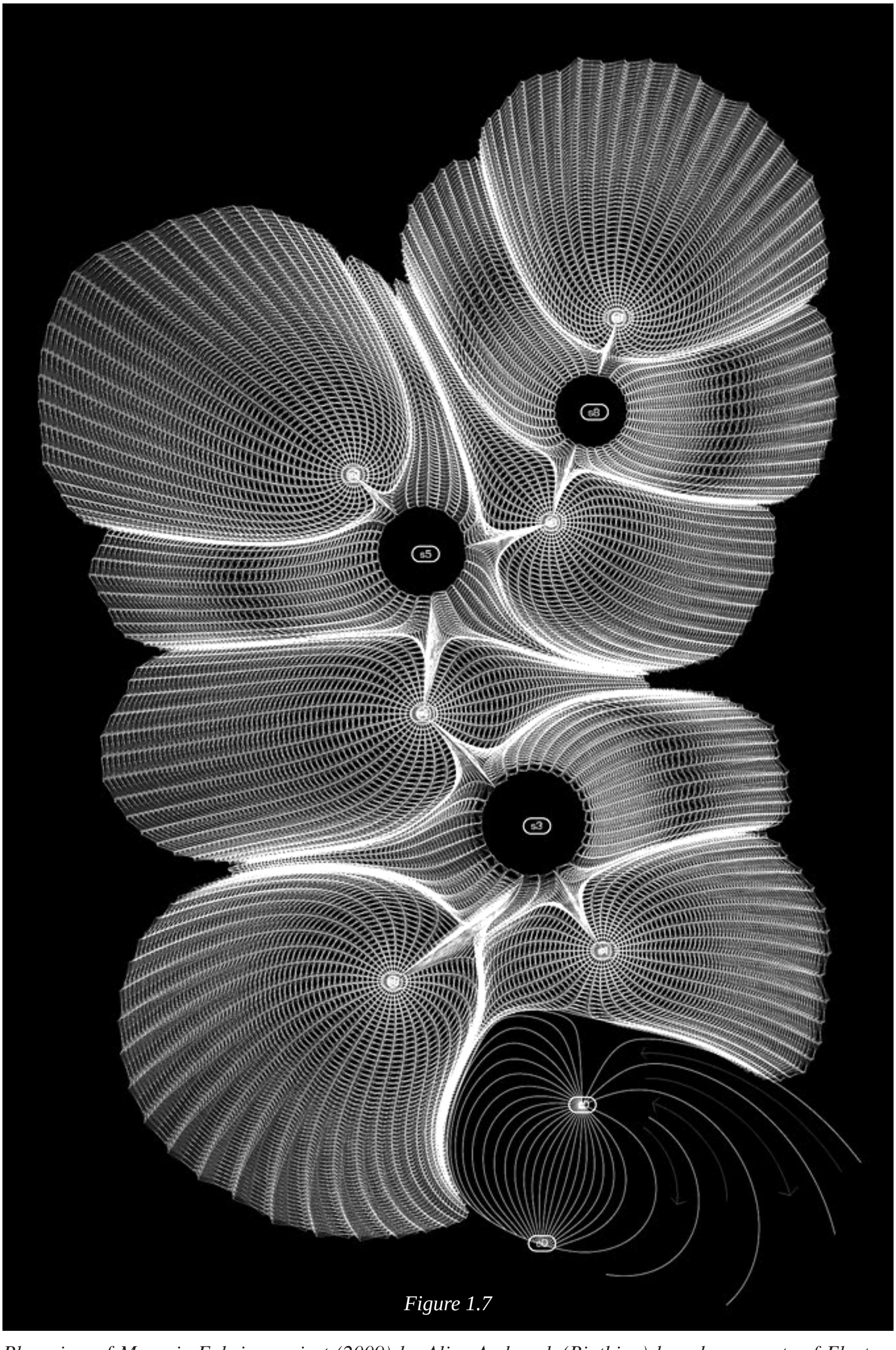


Figure 1.7

Plan view of Mesonic Fabrics project (2009) by Alisa Andrasek (Biothing) based on agents of Electro-Magnetic Fields and Cellular Automata algorithms that form the structural paths of the roofs. Drawing by Alisa Andrasek.

Firstly, Agent-based systems, whose application in architecture (Andrasek 2006; Sabin & Jones 2008; Riiber 2013; Coates & Schmid 1999) includes multiple agents, often hundreds to thousands, which interact based on behavioural rules embedded into every agent [Fig. 1.7]. Agents acts according to local events from which a global organisation is emerging (Weinstock 2010). Such organisational processes are based on computational developed theory by observation of, for example, flocking birds (Reynolds 1987; Bajec et al. 2007) and the movement of ants (Dorigo et al. 2006; Heylighen 2008). From these studies, it is possible to deduct the local and regional behavioural properties of a group of agents that can then be described and explored by computation as powerful formal and analytical processes, often leading to complex visual geometrical organisations, such as those that have been shown by the aforementioned architectural researchers.

Similar to, yet still different from, Agent-Based systems is Shape Grammar, invented by George Stiny and Jim Gibs (Stiny & Gips 1972). These operates with multiple geometrically defined components, though not as behavioural agents, which are combined and propagated based on organisational rules leading to larger wholes from many smaller parts. This is a method for calculation based on algorithmic geometric processes, or composition of styles and languages (Knight 2000). With the foundation in generative processes of geometric entities, both form development and form analysis have been conducted, from painted compositions to large-scale urban organisations (ibid.).

Architectural generation based on the Fractal systems is inherited from biological growth systems (Prusinkiewicz & Lindenmayer 1990; Měch & Prusinkiewicz 1996; Hensel 2006) which explore the ability for a simple element, with often simple rules and a starting point in space, to grow into a larger organisation, based on these three aspects [Fig. 1.7]. The power of the approach lies in its minimal input, with complex and advanced structural organisational output as explored in architectural research by Karl Chu (Chu 2006) Yukio Minobe and Pavel Hladik (Hensel et al. 2010) and David Stasiuk (Tamke et al. 2013) and applied in architectural practice for the creation of structural layout in, among others, the Serpentine Pavilion by Toyo Ito + ARUP [Fig. 1.8] and the façade pattern expressions in the V&A Gallery by Daniel Libeskind + ARUP (Balmond 2002; Leach 2009). The fractal organisation as a whole is based on a linear development in which the articulation at any time is based on the organisation of the previous step of the progressive growth.

The final approach, computational evolutionary systems, was advanced by John Holland in the 1970's as Genetic Algorithms (Holland 1992), which are also adopted in architecture from the description of biological processes. These processes emulate and systematise the genetic procedure of natural selection into digital models that gradually advance towards a goal. In contrast to the aforementioned systems, evolutionary systems operate with two parts, a physical (phenotype) and a metaphysical (genotype). Early architectural research on evolutionary systems was conducted by John Frazer (Frazer 1995) and has recently seen an increase in studies applying evolutionary computation to architectural problems, from the organisation of a spatial programme (Derix 2010) to architectural engineering-based analysis, as has already been mentioned above in relation to the development of structural and energy optimisation methods.

Figure 1.8

Serpentine Pavilion (2002) by Toyo Ito + Cecil Balmond (ARUP) created through a rewriting procedure progressively overlayering square geometries to form a complex structural building envelope. Photo by Jamen Brittain.

The field of computational generative processes based on biological mechanisms is itself growing with numerous sub-categories such as ‘physical algorithms’, ‘probabilistic algorithms’, ‘immune algorithms’ and ‘neural algorithms’ (Brownlee 2011; Shiffman 2012). As these are increasingly becoming accessible and applicable to all fields of scientific inquiry, which deals with complex organisations, they expand both the theoretical and methodological basis of architecture by computational generative processes.

Furthermore, it should be noted that computational paths, while here separated into two orientations, could also be understood as one. This is in fact particularly the case for the agent-based systems, fractal systems and evolutionary systems, as they indeed simulate behaviour and form-making processes in nature, which has then been adopted by an architectural research community in order to move towards engaging complex problems (and complex formal outcomes) in architecture, and to the direct propositions of architectural making.

With the objective of this thesis being to formulate a theoretical and instrumental agenda based on the integration of environments for construction processes, it is necessary to consider, in addition to the initial questions, the following:

What computational methods allow the integration and active influence of environmental aspects on architectural making? (Q8)

And:

What computational methods support the theoretical orientation of Environmental Tectonics as an agenda for a sustainable architecture? (Q9)

1.8 Synthesis

Within environmentally sustainable architectural research, two primary groups of inquiry have been registered. These are the energy-based approaches of Passiv Haus and Zero-Energy Buildings, and the environment-based approaches of Free-Running Buildings and Performance-Oriented Architecture. The former group uses computation to simulate physical conditions and the testing of component physical properties, while the latter, in particular Performance-Oriented Architecture, uses computation as both simulation and generative architectural modalities. As has been argued within this chapter, an environmentally oriented approach, as is identified in the second group, aligns with the objective of this thesis and the associated research questions formulated. However, within these approaches, the formulation of environments appears to remain oriented towards general comfort criteria, rather than the environment becoming the principal driver for architectural articulation related directly to human perceptions. Aspects which are considered constructive, yet indeterminate, have been formulated and specified into the research questions above (Q1, Q4. Q5). These will be addressed in chapter 3 entitled Environments.

The current orientation of tectonics in architecture, and in particular in Digital Tectonics, is oriented towards structural concerns, rather than environmental. However, the shown techniques in which Digital Tectonics advance by computational methods may support a novel environmental approach. This is seen as particularly relevant when aiming to move on from the predominant two energy-based approaches of increasing insulation and sealing built spaces from their climatic and cultural environment. As stated, Digital Tectonics as an architectural discourse is currently based on structural agendas. To approach tectonics as a method for environmental constructions, the above questions (Q2, Q6, Q7) related to tectonics are addressed in chapter 4 entitled Tectonics.

The significant advancements in computational architecture appear to be enabled by adopting simulation systems developed for fields other than architecture, and using generative algorithms that exhibit form-making and form-finding properties. For architectural environmental constructions, advanced by computational processes, as has been done in structurally oriented digital tectonics, it is considered important to examine the specific methods and techniques that enable environmental constructions to unfold. Such aspects of computational integration moving towards novel environmental constructs are central in the aforementioned questions (Q3, Q8, Q9) related to computation and are addressed in chapter 5 entitled Computation.

It is clear that several current research efforts, such as Performance-Oriented Architecture, Performance-Based Architecture and Digital Tectonics, rely on computational and cross-disciplinary approaches. Yet, a series of indeterminate aspects related to environmental constructions are identified. To formulate a theoretical framework for Environmental Tectonics, it is thought pertinent to further examine each of the three fields to identify their integrative potential and to address the research questions posed within this Introduction.

1.9 Hypothesis and Question

To address the field-specific questions listed above under each subject heading and move towards a cohesive theory on Environmental Tectonics, further examinations of the theoretical and instrumental notions within the three fields are made in part 2. Nonetheless, from this initial study of current states-of-art, methods and theoretical orientations in each field, a general hypothesis with a reciprocal research question can be formulated to frame the research and target it towards an integrative approach of interlaying environmental, tectonic and computational aspects.

The amalgamation of the initial questions, followed by the extended questions as laid out above, is hardly possible without losing the depth and width of the task at hand. Nevertheless, the hypothesis and question below form an attempt to encapsulate the central concern and research undertaking.

Environmentally sustainable architecture can be understood as solid, fluid and gaseous matter that interacts, exchanges and forms into structure and space for the betterment of the human environment. Thus, a human-oriented environmentally sustainable architecture can be achieved by the organisation of matter.

Implicit in this is the reciprocal overarching research question:

Can architecture be understood and instrumentalised as the organisation of matter towards a human-oriented environmentally sustainable architecture? (Qx)

The overarching research question adheres to an architectural research approach (Groat & Wang 2011) by being broad in scope while nevertheless framing the theoretical orientation and potential concrete investigations needed to address the question. Importantly, nonetheless, in order to explore the hypothesis/question, a set of specified research questions, which have already been formulated above, are used as building blocks for the conclusion to the overarching question and hypothesis.

2

Methodology

2.0 Preliminary

This chapter intends to clarify and argue for the approach to research taken within the thesis by elaborating on an architectural research methodology that is based on the objective of the thesis. Environmental sustainable architecture, with its broad scope, can be understood differently from the perspective of natural and engineering sciences' intense delimiting into quantitative isolated research inquiries and from the humanistic perspective of inclusive qualitative inquiries. The research design approach is therefore broad in character. However, there is a need for specificity to allow concrete methods of testing, as is central to scientific production. With this in mind, a research position is stated below, which is advanced into a research design. The research design integrates methods and models from the sciences and humanities, with the attempt to address the two objectives of the project being an architectural theoretical framework and a specific set of applied methods and models. The outline of the research methods illustrates a mixed-model approach, including theoretical-conceptual research *into* design, methodological-instrumental research *for* design and experimental-hypothetical reseach *through* design (Frayling 1993). Specific research inquiries within the thesis are approached according to the research method considered most suitable.

2.1 Research span

The thesis is rooted in architecture, with a strong relationship to engineering science, computational science and the natural sciences through biology. While each scientific field could be studied alone with substantial work to be pursued as agendas related to the built environment, it has been a fundamental principle to work across disciplines. This position was elaborated upon in the motivational note and the following project description and successive research questions. It is believed that the correlations and overlaid knowledge fields produce more fertile conditions for a framework description and exploration of what is proposed as Environmental Tectonics. This approach to architectural research is not new and is, if anything, argued to be the most adequate research approach within the field (Groat & Wang 2011) due to its interdisciplinary nature and scope. In terms of the research methodological perspective, the selected methods of inquiry rooted in each of the above fields are utilised as the means of the research work in general.

The objective is not, however, to constitute whether one method belongs more to one field than to another; rather, it is to clarify that the methods have been chosen to support both the broad objective of the project and the specificity of each study.

As the research work will reveal, the project situates itself between the conventional scientific domains of natural sciences and humanistic sciences [Fig. 2.1]. This, as described above, is no different from most other architectural research agendas, though it is important to stress that all studies conducted are based upon this research domain integration, which entails a qualitative reading in art- and architecture-related perspectives and a quantitative approach related to the natural and engineering

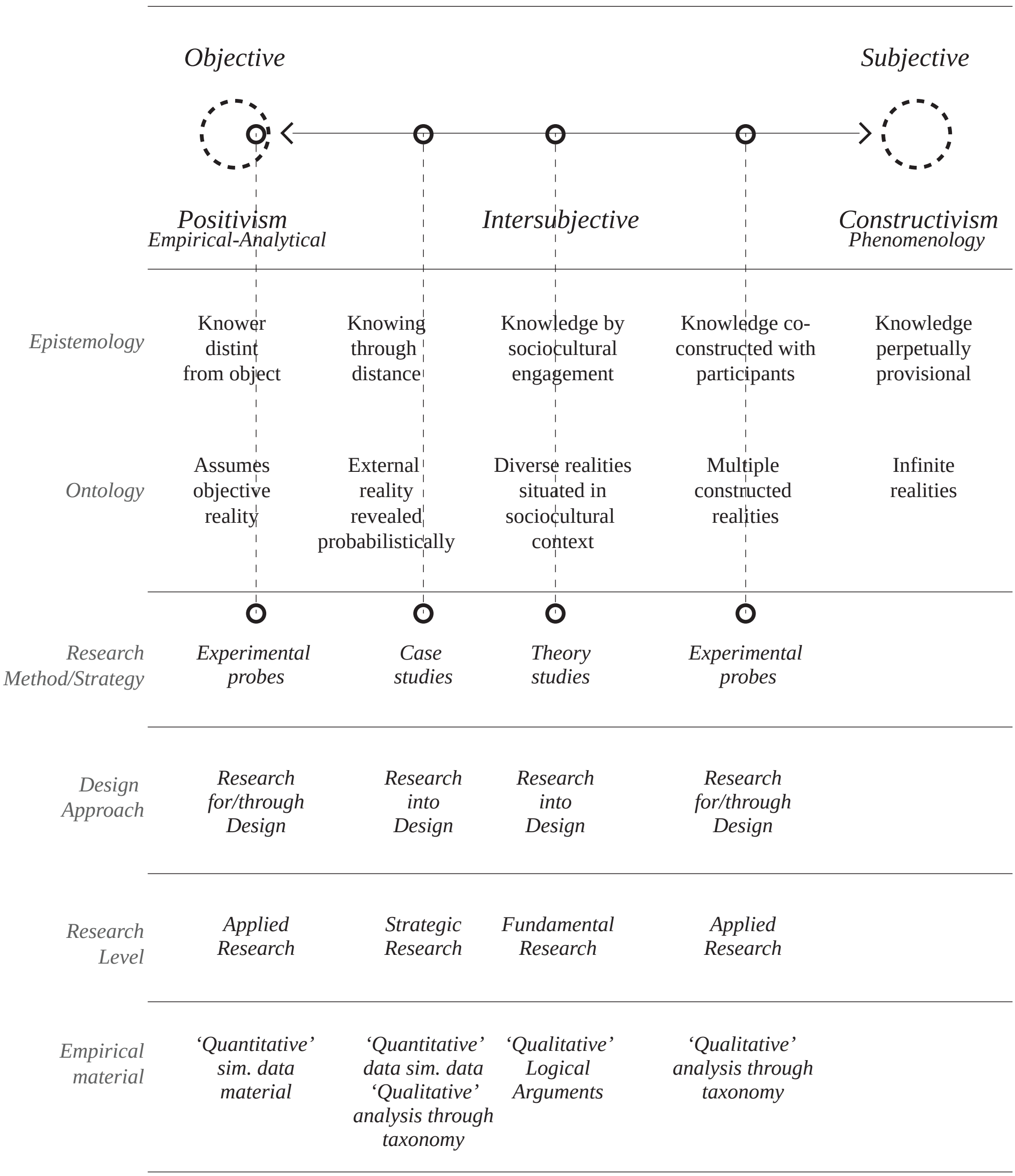


Figure 2.1

Diagram of thesis research philosophy of science positioning based on Wang and Groat's model of research continuum between Positivm and Constructivism research orientations. (Groat and Wang, 2013: 76) Diagram by Isak Worre Foged.

sciences tied together as described below under Research Design. Furthermore, Archer (Archer 1995:3) suggested that the sciences have recently become less reductionist, commonly as a way to isolate and study a subject matter, while the humanities have become more empirically rigorous through the use of information technology. This work builds upon this philosophy of science development.

Yet this work does not suggest bringing either of the research method domains closer together; rather, it indicates that architecture is positioned across both domains at the same time and thus needs to work in both domains simultaneously with the relevant research methods and, from this combination, approaching an architectural scientific discourse. If qualitative and quantitative approaches are used in combination, it is suggested that a highly synergistic potential is reached, allowing a more rich and elaborate research inquiry (Mintzberg 1979; Jick 1979; Eisenhardt 1989:538).

2.2 Research position

Another aspect that should be mentioned is the relatively broad investigative position, which can be described in segments (Archer 1995). A first segment is fundamental research, exemplified by the theoretical arguments and propositions provided in the theoretical chapters. A second segment is strategic research conducted through investigations into the applicability of developed methods to the generation of architectural environmental compositions. A third segment is applied research, in which the work is suggesting explicit applications of a building envelope. A fourth segment is action research, in which physical prototypes are constructed and situated in the environment as demonstrators and for potential observation in a specific context. It has not been attempted to restrict the studies to one research level, but rather the methodological approach to pursue an idea from initial basic observation, its axiom, to as applied a construct possible. This is deemed fruitful, as it allows an exploration of the individual study from different research perspectives and what that might mean in relation to the understanding and development of the overall thesis project. American philosopher of science Eric Winsberg stated the following concept regarding similar approaches:

> *…a form of what philosophers call confirmation holism. Confirmation holism, as it is traditionally understood, is the thesis that a single hypothesis cannot be tested in isolation, but that such tests always depend on other theories or hypotheses. It is always this collection of theories and hypotheses as a whole, says the thesis, that confront the tribunal of experience. (Winsberg 2010:105)*

While the dissertation presents a series of theoretical propositions and specific methods through experiments, it is the accumulated work of the dissertation that amounts to Environmental Tectonics as an approach to environmentally sustainable architecture.

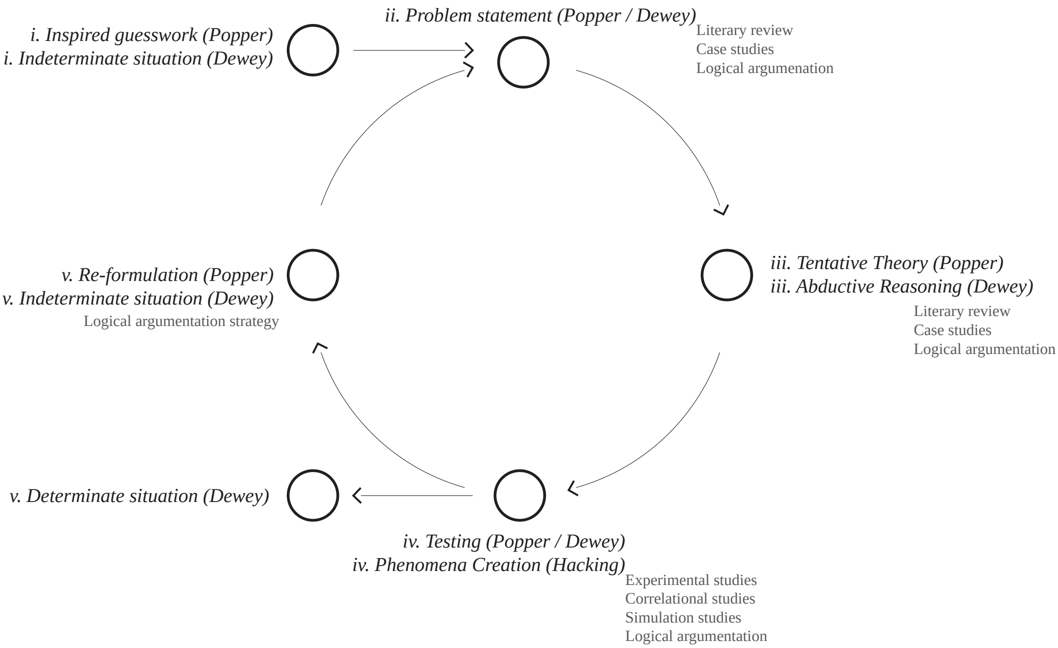


Figure 2.2

Diagram based on Dewey and Popper's cycles of research progression, from axiom indeterminate situations to theory, testing, re-formulation and determinate situations. Diagram by Isak Worre Foged.

2.3 Research Design

The presented work follows scientific conduct by way of a systematic and goal-oriented inquiry from a humanistic perspective, by a systematic analysis of discrete and correlated understanding of the three primary subject fields. The three fields — Environmental Architecture, Tectonics in Architecture and Computational Architecture — are addressed and expanded upon via *'advances by the conduct of logical argument. Propositions are validated or refuted by exemplification and citation'* (Archer 1995:3). And with the same objective from a natural and engineering science perspective, are systematic analysis of observed discrete and correlated phenomena and data-based architectural design experiments conducted.

This largely follows the research approach described by the German philosopher and mathematician Karl Popper (Popper 1959), asserting, beyond his argument of falsification over verification, that the initial research idea is based on 'inspired guesswork' followed by empirical analysis [Fig. 2.2]. From this follows the methodological research cycle of:

(1) Problem statement
(2) Tentative theory
(3) Testing
(4) Re-formulation of problem statement

Problem Statement

Problem statement is also known as hypothesis statement. When converted to an architectural research design, it can be stated as follows.

(1) Hypothesis statement

Hypothesis statement is based upon 'inspired guesswork'. A Popperian formulation of inspired guesswork would be based on rational and explicit descriptions. A different approach is presented by research design author Christopher Frayling (Frayling 1993). He suggests, based on historian David Gooding's studies of Michael Faradays methods, that research, even in the field of natural sciences, is less explicit and more based on imagination and intuition. Such arguments relate the to philosophy of science theories of Thomans Kuhn (Kuhn 1962) and Michael Polanyi (Polanyi 1967). In this work, 'inspired guesswork' is based on previous knowledge, observations and intuitive ideas, initialised from literary reviews and case studies and through classical Baconian observations of the real world, or of simulated worlds.

A further elaboration of this research process, situated in a pragmatic research discourse, is described by John Dewey using the phrase 'indeterminate situation' [Fig. 2.2] to describe a condition wherein a person enters a new situation in which something is unclear when related to existing knowledge (Strübing 2007). The point of indeterminacy becomes the critical context for initiating studies that support the

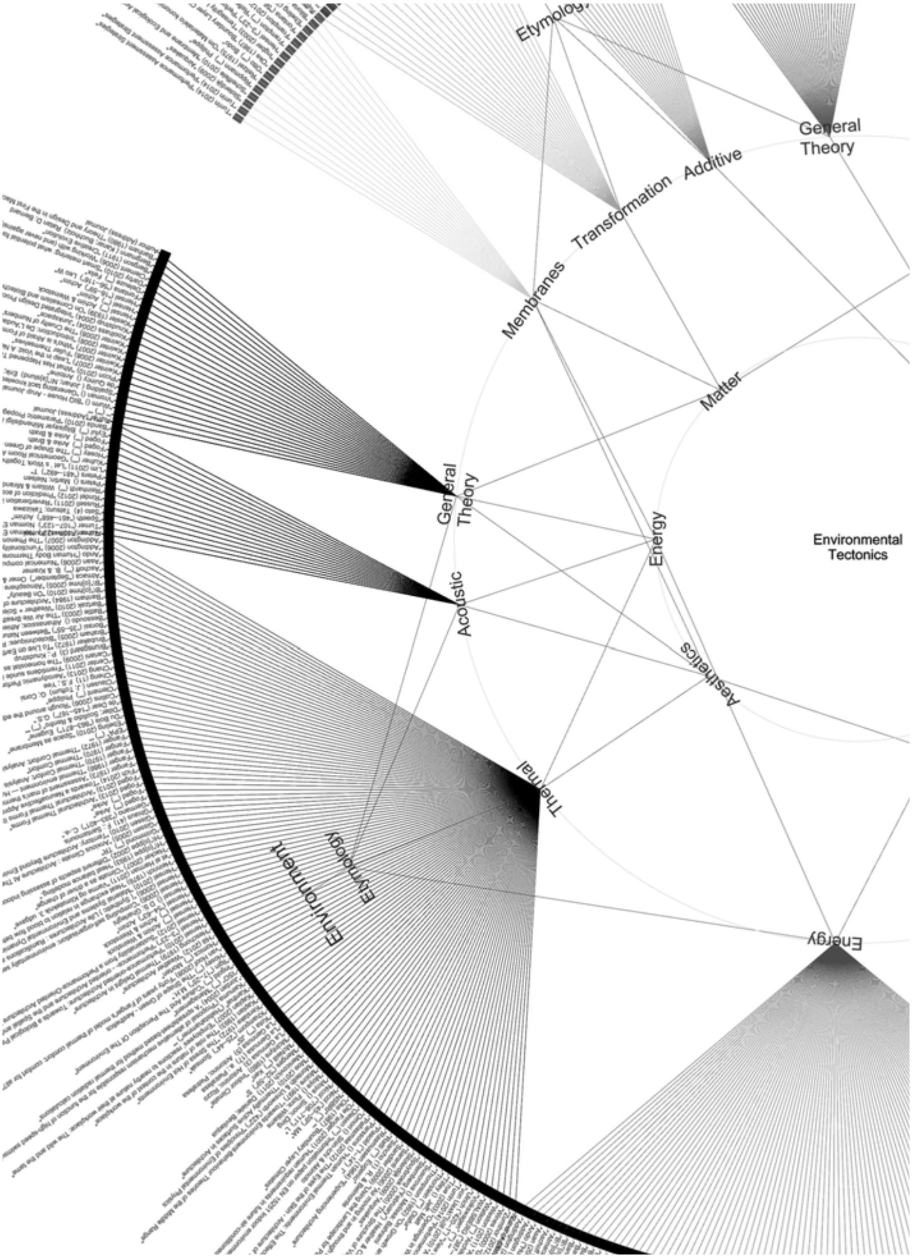


Figure 2.3

Theory Path Mapping of literature sources based on my Mendeley library illustrating the literature segments, relations and platform for a theoretical framework for Environmental Tectonics. The diagram is inspired by the diagram constructed by Christian Norberg-Schulz when illustrating his theoretical path to the formulation of his theories. This is particularly relevant in interdisciplinary work (Groat & Wang 2013:156). Parametric diagram by Isak Worre Foged.

formulation of research hypotheses and questions. The formulation of indeterminate situations is also seen to be operational in formulating the research endeavor as the process of successive steps through normative truths, rather than the pursuit of a singular universal truth determinable by a single all-encompassing research question.

Literary review

Even though the literary review is listed as the first method applied within this thesis, it is not limited to the initial foundation of the project but should rather be seen as a continuously applied method to be used cyclically for explanatory and exploratory actions in its own right and as part of all other methods used in the thesis. While the literature, in principle, is the informational background and qualitative content of the method (Archer 1995), it is not a generally accumulated bibliography. Rather, it is an ever-increasing concretising of literary sources that takes part in shaping the core of the research study during all studies performed as part of the overall project (Wang 2011a:48). In this way, the literary review informs and at the same time helps to identify and formulate the concise and instrumental research question (Wang 2013:51).

As stated above, the literary review for this dissertation is based on a preamble segmentation of the overall field of architecture into the three core literary fields. These fields have been identified through a 'back-and-forth' process (Wang 2013:56) rendering their increasing relevance to the thesis project from previous architectural studies during my MSc.Eng.Arch. project entitled 'Computational Sustainable Architecture' (2008), my M.Arch. project 'Encoded' (2009) and the following two-year research activities focused on adaptive architectures as a university research assistant.

As an instrumental research method in the clarification and dissemination of the literary sources, a specific diagram for the project is produced during and towards the end of the project. The diagrams [Fig. 2.3 and 2.4], represents the selected literary sources of the overall project. These are categorised into subject fields one level under the three primary literary fields, including themes of energy, acoustics, thermodynamics, generative systems, simulation, transformation, et cetera. Sources are considered as input and are organised in a circular form, framing the literary arena of the thesis project. Inside this merged field, theories across the fields are connected to form an increasingly specific notion of the basis for Environmental Tectonics as an architectural approach to environmentally sustainable architecture. The objective of this diagram is to categorise and map the fields of existing knowledge and references into the project and explicate when, and for what, these sources are utilized, supporting the textual formulations. More importantly, it tracks the theory paths and serves indirectly as the underlying structure of the thesis. The difference is that the diagram illustrates a truer web of relationships as a non-linear interlayered platform, while the dissertation is naturally laid out in a linear manner through the linear reading style. This in turn illustrates the holistic research design method integrating multiple and diverse arguments, as stated by Winsberg.

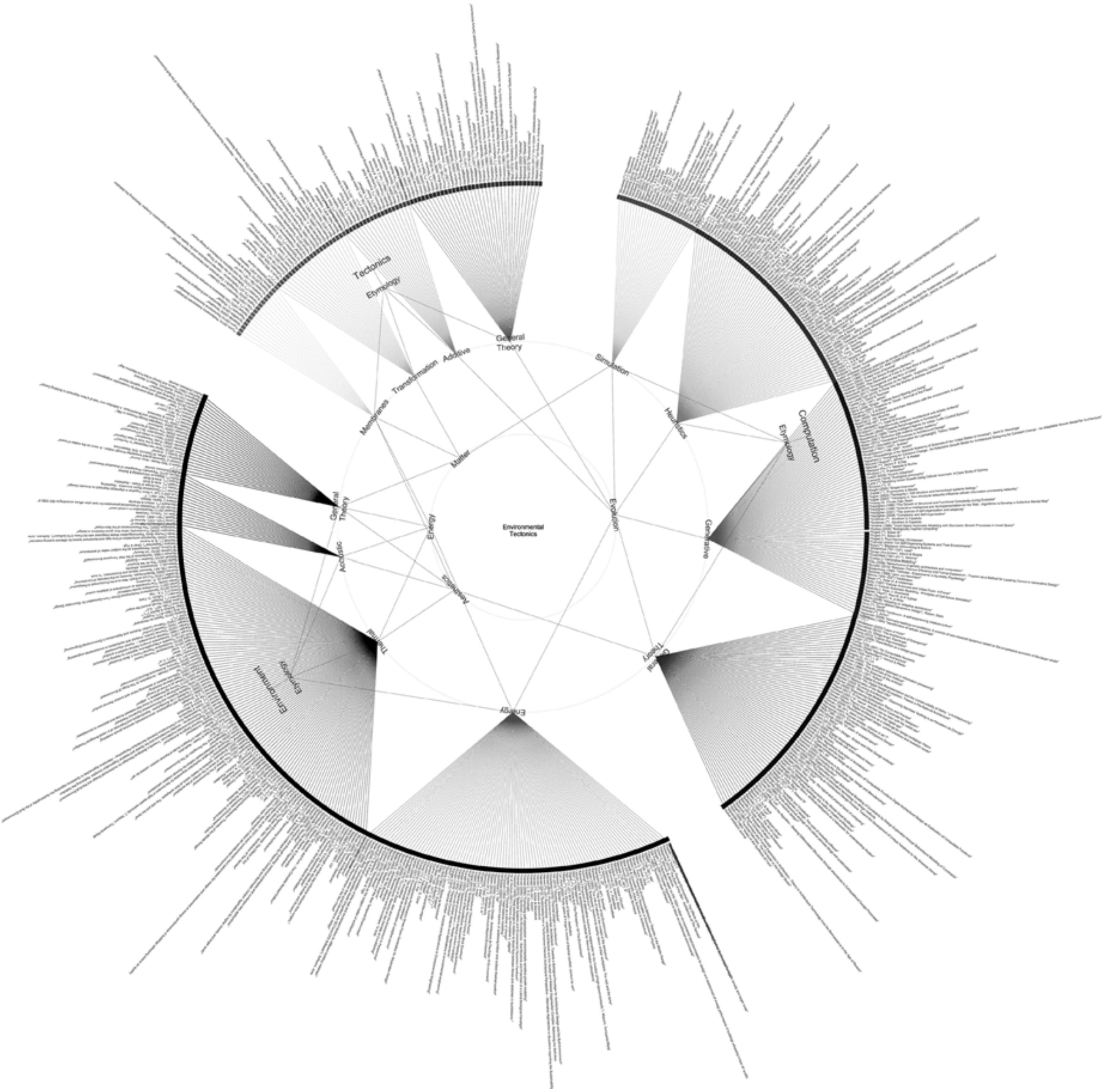


Figure 2.4

An overview of the theory path mapping diagram after 30 months of PhD research.

Case studies

Case studies constitute the method by which the hypothesis statement can be tested. The intention is hypothesis clarification, exemplification and exploration. From Eisenhardt: '*The case study is a research strategy which focuses on understanding the dynamics present within single settings'* (Eisenhardt 1989:534). More specifically, case studies offer the advantage of conducting different investigations within the same example or a few others. Explicitly, it provides and extends the description of the subject, the target being to test preliminary theories or generate theories. (Eisenhardt 1989:535).

While the broad scientific community has accepted the case study as a method for initial hypothesis statement and early formulation of the research problem, significant critique has been raised against the method in later processes of the research, such as verification, falsification and documentation (Flyvbjerg 2006:220). The problem with the method, according to its opponents, is its singularity and context specificity, as is mentioned above. In sum, Danish scientist Bent Flyvbjerg lists five aspects that have demarcated the case study method as a method unfit for scientific inquiry (2006:221). Conversely, it is found that these criticisms can all be refuted and that the case study has indeed been used as an effective architectural research method for theory building, generalisation and documentation (Groat 2011a) from the natural sciences to the social sciences (Flyvbjerg 2006:229).

In this thesis, Flyvbjerg's taxonomy (2006:230) of case study methods is adopted to clarify the case study aim. Here, an 'information-oriented selection' of cases has been chosen, which is based on the aim of maximising the utility of information from small samples and single cases. Within this group, critical cases are selected to achieve information that permits logical deductions of the type investigated. Case studies are used for hypothesis development and theory building in Fields (part 2), from small sample cases related to matter as an environmental organisational principle in architecture and systemised elements as a tectonic organisational principle in architecture. In Probes (part 3), progressive case studies are applied as design experiments of physical and digital probes, allowing the case study method to be used in hypothesis development and theory building and as a test bed [Fig. 2.5].

Observations

Problem statements, or indeterminate conditions, as an axiom for new inquiries are based on observations of all kinds related to the research fields. While typically located in the beginning of a research project, the process of determining indeterminate aspects is seldom bound to the initial phase of problem framing; rather, it is a recurring event in all four phases. This has been particularly visible in the design experiments, functioning as both exploratory and verifying processes of architectural research, often pointing to additional and unexpected problems and unexplainable conditions through simply observing the 'feedback' from experimental models. In this way, observations become the registration of known and unknown phenomena.

Experimental studies	Setting	Strategy / Tactic	Outcome measures
Thermal Tectonics 0	Laboratory	Computational probe > GA Simulations > Energy Simulations	Architecural spatial forms
Acoustic Tectonics I	Laboratory / Field	Computational probe 1:1 Physical probe > EA Simulations > Acoustic Simulations	Architectural spatial forms/structure Simulated measures > Reverberation time (RT60)
Acoustic Tectonics II	Laboratory / Field	Computational probe 1:1 Physical probe > EA Simulations > Acoustic Simulations	Architectural spatial forms/structure Simulated measures > Reverberation time (RT60) > Sound pressure (dB)
Thermal Tectonics I	Laboratory	Computational probe > GA Simulations > Thermal Simulations > Energy Simulations	Architectural spatial forms Simulated measures > Surface/Volume relations for solar energy accumulation > Volume thermal mass for solar energy accumulation
Thermal Tectonics II	Laboratory / Field	Computational probe 1:1 Physical probe > EA Simulations > Thermal Simulations > Energy Simulations	Architectural envelope structure Simulated measures > Comfort temperature (Fanger integration) > Algoritmic responsiveness (iterations) > Construction constraining algorithm domai
Thermal Tectonics III	Laboratory / Field	Computational probes 1:1 Physical probes > EA Simulations > Thermal Simulations > Energy Simulations	Architectural envelope structure Simulated measures > Irradiance/Insolation > Thermal sensation (Fanger integration)
Thermal Tectonics IV	Laboratory / Field	Computational probes 1:1 Physical probes > EA Simulations > Thermal Simulations > Energy Simulations	Architectural envelope structure Simulated measures > Thermal sensation (Fanger+ integration) > PMV/PPD/OP temp > Bonding temperature between layers
Thermal Tectonics V	Laboratory / Field	Computational probe 1:1 Physical probe > EA Simulation > Thermal simulations > Energy Simulations > Thermal monitoring (physical)	Architectural envelope structure Simulated measures > Thermal sensation (Fanger+ integration) > PMV/PPD/OP temp > Layer lengths of composite material

Figure 2.5

Summary of experimental studies, settings, tactics/input treatments and outcome measures. Diagram by Isak Worre Foged.

(2) Tentative theory

A tentative theory based upon the initial hypothesis is elaborated through further description of the hypothesis/problem statement based on literary reviews and case studies.

While the primary hypothesis can be unambiguously expressed, it is not necessarily (though they should be according to Moore (Moore 1997)) possible to test unless it is separated into testable portions through a reductionist approach and (potentially) correlated afterwards, as is common in the sciences.

An example would be to test whether a suggested method, and from it a generated model, can be formulated, on the basis of which it is able to accomplish improved thermal sensation for humans. This is a complex problem to which architectural studies have a typical approach, that is, singular descriptions such as describing the light sensation, rather than a unified measure of human thermal sensation that is based on a more inclusive approach, as is the case with the Fanger (Fanger 1970) equations integrating six different aspects in one description. This statement is elaborated upon in the next chapter. While the inclusive approach offers a more holistic description, the singular description offers a more isolated reply to the problem statement. The more general the hypothesis, the closer it may lie to the nature of architecture as an interdisciplinary field. As an open discipline, which interweaves, adopts and informs other disciplines, it is difficult to meaningfully isolate the inquiry from the many interrelated aspects. The more specific the hypothesis, the more testable it is through verification or Popperian falsification, and thus an architectural research dilemma presents itself. For this reason, the research project attempts to mount a broad architectural framework, which is progressively tested and explored in specified architectural cases and experiments.

Approaching a problem statement that balances these poles of generality and specificity, enabling it to be addressed as part of a tentative theory, David Wang (2013:54) proposes that a problem statement is described in a way that says something about the theme, the elements that need to be studied and how they could be studied. Following the notion that *'a theory is a model'* (Friedman 2003:513), it can be suggested that tentative theories are identical to tentative models. In this line, one can follow Albert Einstein's lead in the description of research models stating that: *'everything should be as simple as possible but no simpler'* (Friedman 2003:519).

Discretising the proposition of a theoretical model into its constituent building blocks may serve to identify key aspects and indeterminate situations during the project development and concluding argument, if the work presented can indeed be classified as a theory (Wang 2013b:76). Gary Moore has defined the constituents as follows:

(a) Proposition,
(b) Logical connections,
(c) A set of conclusions from (a) and (b),
(d) Linkage to empirical reality,
(e) A set of assumptions underlying the theory, and

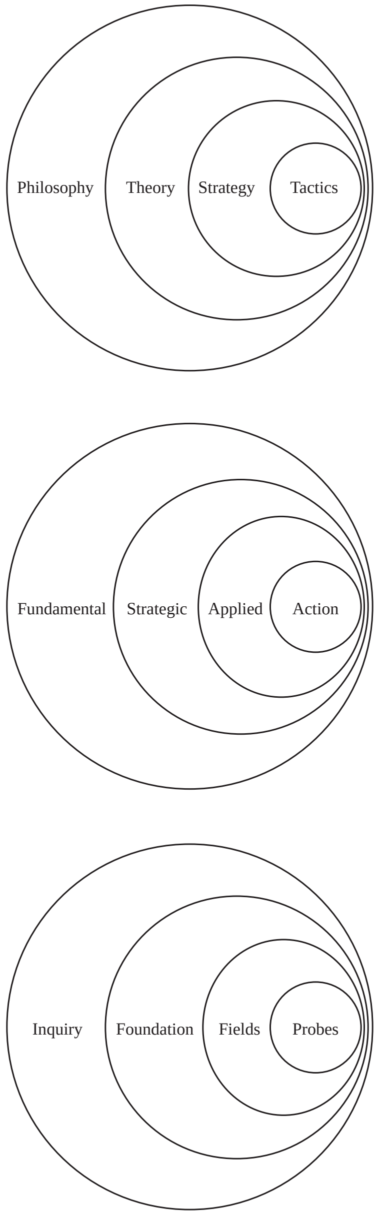


Figure 2.6

Top figure, structure of research levels by Wang (Wang 2011:87). Center figure, organisation of research types. Bottom figure, thesis parts and structure. Diagram by Isak Worre Foged.

(f) Testability of the theory.

From the aforementioned described overall research design, it appears that the research work is geared towards the formulation of architectural theories, which in turn support the claim that the project process and final documentation can be described as a systematic and goal-oriented research inquiry.

The outreach of an architectural theory is important to consider, as architectural hypotheses that are too narrow set the theoretical platform and potential normative truth-finding in a restricted condition, in which the hypothesis can be explicated without studies. Furthermore, an approach that is too narrow limits the potential for a general impact on architecture as a field, as a result defining only what is true for a singular building (Wang 2013b:80). Conversely, a model that is too general may not be applicable to concrete application in architecture and exceeds the ability to be tested. The general hypothesis of this work, that *'Environmentally sustainable architecture can be understood as solid, fluid and gaseous matter that interacts, exchanges and forms into structure and space for the betterment of the human environment. Thus, a human-oriented environmentally sustainable architecture can be achieved by the organisation of matter'* is seen as balanced in relation to the scale of architectural theory building and research approaches. It is not limited to a set of singular buildings or singular contexts; however, it is considered a testable theory due to its ability to be constructed as physical or simulated architectural experiments that relate both to the humanistic sensation of environment and the natural science of energy relationships in discrete and unified methods and models.

While the research is considered a web of knowledge fields, methods and propositions, as stated above, the thesis research and dissertation is constructed in a similar way to the research movement described by Wang (Wang 2011:87) moving from Philosophy, to Theory, to Strategy, to Tactics, reformulated in this thesis as the dissertation parts Foundation, Fields, and Probes [Fig. 2.6].

(3) Testing

Following the research design notation of Groat and Wang (Groat & Wang 2011), the testing of general and specific theories of this thesis is conducted by the use of five research strategies, Experimental Research, Correlational Research, Simulation Research, Logical Argumentation Research and Case Study. These methods are often combined into a mixed-method approach, thus making possible an inquiry that addresses both qualitative and quantitative aspects within the same study.

Experimental research strategy

An experimental research strategy is a *'seeking of causal connections between two or more variables. By the manipulation of a variable within a controlled setting, the effect of that variable's behavior upon other variables are observed, as certain conclusions* *are drawn from these observations'* (ibid). The method serves as a fundamental approach within this work as a vehicle to construct probes of both physical and digital character, which are used as means for verification/falsification and phenomena creation. In all experiments included in this thesis, studies are measured against a base model in order to enable comparative analysis. A comparative analysis can be performed either in relation to existing proposals, such as the comparative analysis between conventional architectural building typologies and the forms generated in the case study of *Thermal Tectonics I* (chapter 9), or in relation to previous versions of the same model, which is the underlying principle of the evolutionary model, as implemented in many of the models developed throughout this research project.

According to Groat (Groat 2013c:253), a further distinction can be made between the types of experimental research work conducted, here roughly divided into laboratory work versus field work. In a laboratory, variables, conditions and constraints can easily be controlled and observed, which allows an improved condition for causal argumentation, whereas fieldwork situated in the 'messiness' of reality is under the influence of many aspects not under direct examination. In this work, all design experiments have been conducted in a 'laboratory setting', on a computer, while several of the successive studies have been further developed for field studies by the construction of physical probes. As stated by Groat, the experience derived from this research shows that physical probes can be difficult to establish as explicit causal models when the investigation objective is to measure and understand environmental aspects related to architecture.

Hence, it can be asked, what is it that makes the physical and representational probe so valuable in environmental architectural research? Philosopher of science Manuel Delanda posited as he explained the mode of operation of experimentalists:

> *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. (DeLanda 2013:172)*

Such an orientation to research inquiry is extensively described by anthropologist Tim Ingold, as he foregrounds making as a way of constructing knowledge in anthropology, archaeology, art and architecture (Ingold 2013). To Ingold, direct making, a form of experimenting, is central to the ability to understand and construct knowledge beyond information.

The theoretical/computational model of the case study *Thermal Tectonics II* (chapter 10) gained, in this manner, significant input from the physical probe. However, this input came not from the registration of environmental performance but, as will be explicated later, from the reformulation of the algorithm devising the rotational position of a brick. This created the basis for a redefinition of the algorithmic solution space, understood during the physical construction of the brick wall. The same can be said for the model of the case study *Thermal Tectonics IV* (chapter 12), where the making of the physical probe resulted in discussions on the manufacturing processes of the bi-material composites. This introduced the aspect and impact of gluing temperature on the bending capacities, which subsequently could be explored as an extended dimension within the digital probe. This in turn allowed a much-improved architectural method and increased solution space, permitting a more generalised application through specification of the variables at work. These physical probes allowed the *Thermal Tectonics IV* study to progress across three phases, with each phase identifying new aspects for each physical setup.

Other examples can be provided by descriptions of mathematics-based core methods in science, as these lend themselves to the same use of experimental side effects and additional gains by the experimental approach, as they serve to identify, present and argue for indeterminate conditions. Charlotte Bigg pointed to prominent physics research methods for the understanding of physically complex phenomena, such as Brownian motion, by the use of visual representations.

> *Einstein's and Perrin's Brownian motion work is justly famous for raising a number of issues central to the epistemology and historiography of the physical sciences, in particular, related to the nature of evidence, the relationship between theory and experiment, and realism. Rather than investigating the detailed ways in which a perfect fit between Perrin's experiments and Einstein's theory was realized, this paper explores the gap …. (Bigg 2011:157)*

In architectural practice and research, such methods are increasingly used to address issues of communication, analysis, synthesis and simulation, allowing a visually-based approach of examination to be paired with experimental modeling of architecture (Achten 2009).

To delineate the experimental approach in this work, there has been a goal of maintaining the architectural envelope as a subject for experimental testing of general and specific questions, thereby concretising the experimental studies into one architectural element. This carries the advantage of continuous investigations of the general research inquiry through a specified object addressed by different measures. The reason for choosing the envelope as the primary means for describing Environmental Tectonics is further elucidated in part 2, Fields.

Correlational Research strategy

From an experimental probe as a vehicle for investigation, it is possible to identify differences and weights of the design variables in each specific study, or, more specifically, relationships studies (Groat 2013b:212). This includes, for example, studies of the effect of spatial geometry related to material sound absorption and algorithmic search performance in the case studies *Acoustic Tectonics I* and *II* (chapter 7 and 8) or studies through sensitivity analysis of the six factors determining thermal sensation as explored in the experimental studies of *Thermal Tectonics II, III, IV* and *V* (chapters 10 to 13). The correlational method is additionally used to construct the boundary conditions for a logical argumentation model described below by determining what aspects might assert the largest influence within a system. An advantage here is to reduce the variables that constitute a research model while, nevertheless, maintaining the diversity required for the specific investigation. This aspect has been emphasised with the quotation from Albert Einstein stating the importance of model simplicity. Another aspect, perhaps most known in relation to correlational research methods, is the ability to trace patterns and thus identify variable behavior.

The specific tactic of this strategy is to use mathematical models based on previous empirical studies. These are paired with architectural experimental models, computational probes, intending to reveal the capacities of the variables in relation to the general hypothesis of the project and the specific aim of each study.

While this method does not allow for the exploration of a given problem in depth, it helps to clarify relationships between constituents of a given method and model. This allows for improved further studies during the construction of an instrumental model and simulation. Further, Linda Groat (Groat 2013b:238) argues that causality is not observed in correlational studies, meaning that it is possible to determine what is happening but not why it is happening.

Simulation strategy

The presupposition for simulation research is that knowledge of ‘a reality’ can be obtained by reproducing that reality in some substitute medium. David Wang has stated, *‘In a general sense, simulation research is useful both in developing theory and in testing theory…This is particular true for theory-driven proposals for how physical environments can enhance (or otherwise alter of benefit) some aspects of life’* (Wang 2013b:278). More specifically, in this work, mathematical simulation models are used on the basis of their ability to capture real-world relationships with abstract numerical expressions (Clipson 1993). While most aspects of analysis, such as reverberation time for acoustics and mean radiant temperature for thermal sensation, are based on mathematical descriptions, other parts of the utilised and developed methods and models cannot be said to be limited to analytical mathematical and numerical expression. Several simulation models of this work are based on algorithms, which can be described analytically through mathematics, but are based on logical procedures with solving properties, such as evolutionary algorithms. These simulation models are explicated in part two, Fields, in the chapter entitled Computation (chapter 5).

Claims to the imprecision of simulation as a research method have been made, based on the lack of interference with the real world as compared to physical experiments. This, however, has subsequently been refuted by the explication of the reductionist procedures that are often a necessary part of constructing a physical experiment, while a simulation can be more inclusive (Winsberg 2010:61). While this is certainly the case for the investigation of ‘intergalactic gas exchange processes’, it is arguably, in architecture, a rather different case, as the objectives of architectural inquiry are more tangible and compatible with physical experiments. Nevertheless, simulation is used as a method throughout this thesis, to pair generative and evolutionary processes (these being simulations in themselves) with environmental simulations. Inquiries with this objective would simply not be possible to pursue by way of physical experimentation on an architectural scale. Secondly, the simulation enables prescriptive research, in that it supports complex non-linear time-based integration processes. Within these processes, the mere complexity and timespan considered would be, if not impossible, infeasible in physical models.

In support of this approach, the aforementioned philosopher of science, Eric Winsberg, in his book *Science in the Age of Computer Simulation*, elaborated further on the notions and implications of simulation methods as an approach to research (Winsberg 2010). Numerous examples supporting the claim are given illustrating simulations as a method for hypothesis generation, theory building, verification and validation, thus underlining an epistemology of simulation as a whole. Beyond these aspects, he demonstrated the need for representational methods used by the simulationist. As data is produced during simulation, it can only be observed and understood through a conversion to visual identification of the human who interprets and potentially interacts with the simulation outcome. While this aspect may seem secondary, the success of simulation as a research strategy for observation of phenomena relies heavily on the graphical communication of data (Winsberg 2010:18). This aspect is discussed further in relation to the theories in part 2, Fields, and the architectural experiments of part 3, Probes. Simulation is used predominantly as a tactic related to experimental research and the construction of 'Logical Argumentation' models.

Logical Argumentation strategy

'Logical argumentation models attempt to situate a well-defined thing or issue in a systemic framework that can have explanatory or utilitarian power over all instances of that thing or issue' (Wang 2013b:301). In this sense, the method aligns with the objective of the project by attempting to establish a framework that includes both a theoretical platform and a set of instrumental approaches. The method supports the interconnection of three architectural fields where the instances presented in each field can be traced back to isolated empirical appearances, either directly, by case studies, or indirectly, through previous observations by others.

The logical argumentation strategy is therefore not bound by testing phases but applied throughout the thesis, operating at different descriptive and explanatory levels. In each of the three chapters of part 2, discursive language is used to anchor and position sub-fields, such as 'energy', in the definition of Environments as a whole. The discussion moves up a level in the following chapter, entitled Correlations, where the different Fields are situated into juxtapositions. Here, primary logical systems (Wang 2013b:305) are formed, which serve to construct a broad theoretical platform for instrumental and testable models related to quantitative methods, as described above under simulation strategies. Specifically, the primary platform is used as a normative basis for the work presented in part 3, Probes. This, lastly, through the accumulated work, constructs the synthesis argumentation as a framework for Environmental Tectonics.

The robustness and clarity of the logical argument are based on its definitions and its relationships. Definition is *'the conceptual delimitation, in the form of words or signs, of the scope of a system as well as its constituents'* (Wang 2013b:312). This means using exact formulations of a given term, resulting in this work in etymological studies within each of the three theoretical fields. For this reason, the definitions provided in part 2, Fields and Correlations, are elaborated to construct the theoretical chassis, which also includes sizeable technical nomenclatures.

Relationship is '*a systemic framework that must demonstrate certain rational propositions that go a long way toward making the system logically coherent'* (Wang 2013b:316). From relationships, we are able to establish conclusions from deductive reasoning, performed in different case studies presented in part 2, Fields. These are descriptive processes; however, as the project also aims to be instrumentally prescriptive, induction is used, as a basis for later experiments. This combined duality of deductive and inductive procedures is considered stronger from a research perspective, as the risk of stating the obvious during deduction and the risk of contingency – uncertain prediction – during induction is addressed within the same project (Wang 2013b:317).

Important to mention is the ability of the Probes, not only to exemplify and potentially verify or falsify the logical argument presented in Fields and Correlations, but also to question, explore and extend other aspects of the logical argument, which is not accessible through overarching larger discursive arguments alone. This assumption as a research strategy is elaborated upon below in Verification, Falsification and Phenomenon.

(4) Re-formulation

Upon testing, by its various methods described above, a new singular condition or a series of indeterminate situations may be identified, which enabled the process as a research cycle when re-questioned. Re-formulation of the research question and inquiry thus entails not only a rephrasing, but also further critical delineation. In this work, both conditions are present, in which an identified aspect can be addressed in a subsequent experiment, while other aspects are investigated in later experiments.

Part 3, Probes, while progressive in character, illustrates how it has been necessary to distill some aspects for later studies to maintain a specific examination throughout the project. In the same manner, some indeterminate aspects and questions that have been identified but not further addressed within this project inevitably point to further research work beyond this thesis. Importantly, this also illustrates the nature of experimental research, as the notions of verification and falsification do not stand alone but rather, to a large degree, are paralleled with phenomenon identification and creation.

2.4 Verification, Falsification and Phenomenon

While case studies can be seen as biased towards verification, it is often the case that they, surprisingly, result in falsification (Flyvbjerg 2006:235) of the studied subject and thus present new conclusions and new insight. This process allows for not only a verification or falsification, which initially can be seen as the aim of presenting a research hypothesis, but also, according to philosopher of science Ian Hacking (Hacking 1991), a much-overlooked aspect of research, namely the construction of phenomena, creating the potential for new insight and further studies. Hacking argues for the observation of unexpected phenomena as an essential aspect of research in that it reveals potential elements that are otherwise intangible. Thus, two research strategies relevant to this thesis related to phenomena in architectural research can be mentioned. Firstly, instead of dismissing non-explanatory noise or abnormalities within a research study performed as experimental error, these factors can become a source for new investigations. Secondly, this approach can be activated, rather than being a by-product, in which studies can be performed to allow the potential creation of phenomena as a catalyst for new insight. This approach is linked closely to current architectural experimentalist research agendas through the construction of research probes with the objective of phenomena creation aligned with the objective of verification or falsification.

While natural science aims to understand and explain phenomena that can be observed, an architectural science may allow the pursuit and understanding of what we are unable to observe directly. This statement relates to Herbert Simon's notion of the *'science of the artificial'* (Simon 1996), or everything that is not to be observed in nature. This is the case with fields such as economic systems and cultural systems, in which phenomena can be derived from nonexistent future conditions, hence not observable, unless prescribed within a given system. An architectural scientific agenda, being, among others, related to both economic and cultural prescriptive systems, may therefore position itself as much by the creation of phenomena to understand potential paths ahead as by verification and falsification of existing conditions.

In this context, Tim Ingold promoted the notion that knowledge growth could be achieved by positioning the research method to learn something 'from' what is studied, rather than only about 'what' is studied (Ingold 2013:8). This, he stated, is particularly linked to practical making processes that enable knowledge growth processes while inside the inquiry, rather than observing it from afar. As a making action is carried out, the active engagement increases the ability to understand what aspects that might be indeterminate, using Dewey's terminology, instead of understanding what was intended to be studied at the inquiry's outset. Hence, the active engagement within architectural research by experimentation may promote architectural findings that would otherwise not be tangible.

2.5 Conclusion

With the intent to approach architectural research through the building of a theoretical framework and distilled specified instrumental experiments, a set of scientific methods have been selected for the purpose of the intended research. This entails a broad set of epistemological and methodological approaches, which, according to Wang and Groat, serves architectural research well. While part 2 of this thesis is strongly theorist-oriented and part 3 is situated in an empirical experimentalist approach, the epistemological foundation remains the same.

While the research approach of Popper and Dewey can be seen as a linear, cyclical process, it can also be understood as nested cycles, in which a cycle is situated within another cycle. The overall objective of the thesis can, in this way, be understood as an overarching cyclical process, while each case design research study and experimental setup can be understood as the same cyclical process, but imbedded into the larger process of theory building, testing and reformulation, by verification, falsification and phenomena creation. As theory building has been advanced by experimental studies and experimental studies have been challenged and formed by theory, this non-linear, at times disconnected research application seems more adequate to the nature of architectural research – or at least, that is the tacit experience of this thesis.

3

Environments

3.0 Preliminary

While Free Running Buildings and Performance-Oriented Architecture approaches are currently advanced by the mentioned authors, it was in the Introduction chapter discussed how architectural research and practice is centred on an energy-efficiency-based approach to environmentally sustainable architecture. This points to an increasing adoption of technically oriented methodologies, rather than a human-oriented environmental architectural methodology. From this position, an initial question was posed that frames how environments for humans are constructed by asking:

> *How can environmental constructions enrich human-perceived environments?* (Q1)

The question is addressed in this chapter, particularly in the section *Notes on Environments*, by analysing and elaborating upon theories rooted in biological, neurological and architectural domains. The intention of this section is to get closer to an understanding of why and how we perceive and approach environmental constructions for humans, as a prerequisite for an environmentally sustainable architecture.

Following this examination, the chapter proceeds towards offering an instrumental approach to the notions above and how they can be integrated into architectural design models by asking:

> *How can analytical and numerical methods of human sensations of the environment be integrated into the architectural conceptual design phase?* (Q4)

And:

> *How can the relation between a structure and an environment be understood for environmental constructions?* (Q5)

These questions are addressed in the sections Material and Energy and in particular in the section Modelling Environments, rooted in theories from biological, engineering and architectural domains. The intention of these sections is to get closer to ways of implementing the intended architectural environments into form exploration and form analysis methods and models, which will be advanced further in the chapters Tectonics and Computation.

3.1 Notes on Environment

An architecture oriented towards the climatic environment references a broad understanding and points to different aspects of what surrounds us. In architecture, the climate, the weather and the environment are often interchangeably applied as terms (Hill, 2012). However, from an etymological standpoint, climate means *'the weather conditions prevailing in an area in general or over a long period'* (Oxford Dictionary, 2014). Thus, climate is a general description of weather, meaning, in reverse, that weather is a specified climatic condition in a small time span and defined by local specificity. The etymological wording states, *'the state of the atmosphere at a particular place and time as regards heat, cloudiness, dryness, sunshine, wind, rain etc.'* (ibid, 2014). In this definition, atmosphere is added to the list of notions that are of interest to this work. Atmosphere has two meanings, *'the envelope of gases surrounding the earth or another planet'* and *'the pervading tone or mood of a place, situation, or creative work'* (ibid, 2014). Before investigating the meaning of atmosphere in more depth at a later point, focus is placed on climate and weather. The revision then returns to atmosphere, to then move on to the notion of environment which also holds two meanings, *'the surroundings or conditions in which a person, animal or plant lives and operates'* and *'the natural world, as a whole or in a particular geographical area, especially as affected by human activity'* (ibid, 2014).

Climate

From climate to environment, through weather and atmosphere, an increasing role of the human is defined as an active agent of influence in the creation of the respective phenomenon. As has been previously mentioned, human activity has risen to the power of significant climatic influence, beyond weather monitoring. This is done by actively modifying the constellation of the atmospheric composition by utilising chemical processes on a large scale. Such undertakings are not new; they include the deliberate change of moisture content in cloud layers by seeding silver iodide, also known as 'cloud seeding'. This means to directly modify the Earth's atmosphere, as has been practiced for military purposes for at least fifty years. The effect and affect of such approaches can be powerful to the human, as asserted below.

> *Scientists discover that sprinkling pure silver diodide into clouds would demonstrably boost the resultant precipitation. Led to 'cloud seeding' for both military and civilian use. From March 1967 until July 1972, the US military Operation Popeye cloud seeded silver iodide to extend the monsoon season over North Vietnam, specifically the Ho Chi Minh Trail. The operation resulted in the targeted areas seeing an extension of the monsoon period, on average, of 30 to 45 days. (Bartzak, 2010:45)*

This form of climatic regulation has been seen in numerous examples (Bollozos, 2010) of experimenting with very large and very complex natural processes for the effective conditioning of individuals or a group of humans. German philosopher Peter Sloterdijk elaborates on the extremity of climate control and the ability of humans to regulate the invisible mass that we occupy.

> *The horror of our epoch is a form of appearance of the theoretical-environmental modernized science of extermination, thanks to which the terrorist understands his victims better than they do themselves. When the body of the enemy can no longer be liquidated with direct assault, the possibility presents itself to the attacker of making his existence impossible, by immersing the enemy in an unlivable milieu. (Sloterdijk, 2009:44)*

This forceful approach of regulating the climate on this scale in relation to architecture remains unproven; however, the technological method of regulating moisture content in a defined space, through a mechanical system, has been widely accepted in the built fabric, as implied in the introductory chapter.

The consequent issue of the above immersive approach to climatic control, and in relation to architecture, is the non-defined and non-controllable boundaries. The climate is strongly influenced but only vaguely controlled on the human scale. This is in contrast to the architectural wall as defined by way of a separator (Evans, 1971), which makes a clearly defined edge control of such regulated climates. A second issue is the verticality of climates that is not commonly considered in architecture, as architecture primarily operates close to the surface of the Earth. Hence, in architecture, an understanding of different climate patterns is generally based on the position on Earth, described through latitude and longitude notations. The notations form a two-dimensional environmental map wrapped around the globe, but omit from these coordinates the vertical structure of the climate, the atmospheric layers arranged perpendicular to the surface of the Earth. These atmospheric scales and limits are divided into Micro-scale (10^{-2} to 10^{3} m), Local-scale (10^{2} to 5 x 10^{4} m), Meso-scale (10^{4} to 2 x 10^{5} m) and Macro-scale (10^{5} to 10^{8} m).

At Macro-scale and Meso-scale, large climate phenomena take place over longer periods of time, such as weeks, months or years, while the lower Micro-scale and Local-scale, which form the Troposphere extending from the Earth's surface and 10 kilometres upward, take place over days, minutes and seconds. Within the Troposphere a series of environmental layers are organised to form the planetary boundary layer, which has a diurnal displacement between 100 metres and 2 kilometres from the Earth's surface. A turbulent surface layer is formed within the boundary layer based on the surface roughness of the Earth and convections, with a displacement between 2 to 50 metres. A roughness layer is formed within the turbulent layer, which is defined by the roughness of the Earth (from trees, vegetation, et cetera) and stretches 1-3 times the height of the roughness objects. Lastly, a laminar layer is formed directly connected to the surface. This layer is only a few millimetres thick and acts as a non-turbulent buffer between the surfaces of the Earth and the objects and the layers above it (Oke, 1987:5).

From a vertical- and horizontal-scale perspective, it is the boundary climate layers and their dynamics within a given time period that relate to the built fabric, seeing

Figure 3.1

The New York skyline represents an example of a climatic context, which is influenced by a climatic vertical dynamic system. Photo by Isak Worre Foged.

that architecture to a large degree is created below 50 metres from the Earth's surface. However, as cities become denser, high-rise buildings become more common. This alters the climatic context into an intensified vertical differentiated climatic condition. From this, the extension of the roughness layer of the Earth is moved, and new boundary layers are created on the new topography created by vertical buildings [Fig. 3.1]. The climatic context for buildings in urban zones becomes, in this way, more three-dimensional and continuously locally specified by the addition of vertical structures.

Additionally, when observing environmental scales through a time period of one day, the transformation of what is often considered and simulated as static environments appears extensively dynamic. Environmental scientist T.R. Oke illustrates this effect by demonstrating the diurnal dynamics of an organisation of a mountain-valley wind system, which is caused by temperature deviations. The wind direction reverses along the valley and perpendicular to the valley direction along the uphill/downhill surfaces of the mountain and in altering altitudes depending on whether it is night or day (ibid:178).

A perhaps more well-known example is visible in coastal zones due to the storage and release of solar energy in water and land areas. While receiving the same quantity of solar energy, the distribution of material, water and soil, in different areas, creates enough difference in energy fields to diurnally reverse wind directions locally (ibid:168). When defined, as it is here by Oke, it is referred to as a weather condition induced by the climatic conditions.The properties of scale and boundary layers and their effect on the environment are similarly present in buildings, vegetative structures (with even more complex layer structures) and animals, inducing different weather phenomena based upon their form and ability to store and release energy (ibid:111, 220, 268).

As mentioned, when the built fabric is constructed, it is embedded into the Earth's surface properties roughness layer, taking part in determining environmental climatic phenomena between 2-50 metres from the surface. This can be suggested as a passive modulation of the micro- and local-scale climates and thus indifferent to the macro- and meso-scale regulation of the chemical cloud seeding example given above. While macro-scale climate regulation as a strategy for architecture remains an unexplored pathway whose exploration is not within the scope of this work, it can also be argued that this form of regulation reduces the mandate of architecture to condition humans. In turn, French horticultural engineer and researcher Julés Clement proposes how climate should take part in humans' understanding of nature.

> *There is in nature, as with the weather a theory of chaos, and I find very pleasing that which is unpredictable, that which we cannot completely anticipate in our predictions of what will happen tomorrow. One can only project or hypothesise, knowing that nature will frustrate any hypothesis we put forward. (Clement, 2006:91)*

This evidently puts architecture into a bit of a passive role. Nonetheless, one can propose that Clement's position supports the development and evolution of architecture, as it

Roof of the Nordic Pavilion at the Venice Biennale (1958) illustrating the cross layered beams, which create the translation from strong, sharp and direct light to indirect and diffuse light conditions. Photo by Åke Eson Lindman.

must adapt to local and changing conditions mediating between climate and humans over time. This notion points to the effect of weather, being time and climate-specific, and the capacity for architecture to take part in its modulation.

Weather

British architectural theorist Jonathan Hill is particularly aware of the notion of weather, over the notion of climate, as he posited:

> *In Weather Architecture, the relationship between architecture and the environment is one of mutual dependence, which requires the architect to develop a subtle and complex understanding of time and context, accept the inevitability of unexpected change and acknowledge weather's creative influence. (Hill, 2012:5)*

Hill points, in citing examples, to the Norwegian architect Sverre Fehn, who designed buildings for very different kinds of weather and actively understood and not only integrated the weather as an element of his work but, as Hill posited, allowed the weather an authorship role in the making of architecture. This comes to the fore in the most elegant manner in the Nordic Pavilion [Fig. 3.2] designed for the Venice Biennale in 1958. Here, large cross-layered vertical concrete beams change the sharp and contrast-inducing Mediterranean light and shade to the Nordic soft and faded light conditions. Hill elaborated:

> *For an architect concerned with the subtleties of daily life in a harsh climate, actual immersion in nature is not an option. Instead, Fehn and Lewerentz recognised weather's metaphorical potential, making the evocation of a weather condition the purpose of a building. In a milder climate, Fehn combined architecture and nature to the extent that Nordic light became the Nordic Pavilion's principal material. (Hill, 2012:286)*

The changing conditions of weather based on time and place thus receives, in the work of Fehn, another transformative process before it meets the human observer. This constitutes a reciprocal relationship even at a relatively small scale in that the building actively modifies its weather. As illustrated above by Oke, the weather actively modifies the building to the level of its direct materialisation, as designed by Fehn and asserted by Hill. While Fehn illustrates the use of weather by understanding the local climate rhythms and properties, translated into a mediating construction between weather and human, other more active strategies of understanding and applying the components of weather to comfort humans have been utilised since the time of the Romans. As they understood the impact of light, temperature, humidity and air velocity on the human body, the Romans designed well-defined spaces, by their proportions, organisation and materialisation, to construct a specified weather suitable for the activities of Roman society. Indeed, the construction of the thermal baths

Figure 3.3

Roman bath and a human being immersed into the moist conditioning and the perception of articulated thermal environments. Photo by Ben and Viv.

shows not only the understanding of what affects humans, but also the understanding of thermodynamic potentials of radiation (Moe, 2010). This in turn enables the users of the bath to position themselves to locally regulate humidity and temperature levels [Fig. 3.3].

Another approach to the activation of weather and its elements in architecture can be observed in the more contemporary Blur Building [Fig. 3.4] project by American architects Diller Scodifio + Renfro, designed for the Swiss National Expo in 2002. By the use of a mechanically driven system, water is sprayed to create a fog surrounding the skeleton of the structural design. Situated in the water of lake Neuchatel, on an open plane, the building itself creates the fog. Nonetheless, this materialisation is intensely open to wind direction and speed, forming the ephemeral material by an interaction of man-made and naturally occurring weather conditions. The meeting between a high-resolution controllable grid of nozzles and the 'porous' properties of the fog points to the two-fold, articulated and operable systems fragility when situated in the surrounding natural and uncontrolled weather and the interaction of natural weather patterns with the created fog. In contrast to the approach of the Romans, the Blur Building is not framed by walls, but entirely open, receptive and fully influencing the human perception of the local environmental condition in alliance with the weather conditions. The architects elaborated on the intention and properties of the building.

> *The Blur Building is an architecture of atmosphere - a fog mass resulting from natural and manmade forces. Water is pumped from Lake Neuchatel, filtered, and shot as a fine mist through 35.000 high-pressure nozzles. A smart weather system reads the shifting climatic conditions of temperature, humidity, wind speed and direction and regulates water pressure at a variety of zones. Upon entering Blur, visual and acoustic references are erased. There is only an optical "White-out" and the"white-noise" of pulsing nozzles. Contrary to immersive environments that strive for visual fidelity in high definition with ever-greater technical virtuosity. Blur is decidedly low-definition.*
> *(Diller, Scofidio, & Renfro, 2002)*

In describing the level of immersion experienced by the occupants of the building, the architects reminds us of the deep relation created between the weather, the building and the human.

> *Water is not only the site and primary material of the building: it is also a culinary pleasure. The public can drink the building. (ibid.)*

In the above three examples, weather and its properties are utilised as the principal aspect of architecture in determining the visual, thermal, tactile, audible and olfactory reading of place and time, by modifying the light condition in the Nordic Pavilion or by controlling moisture and radiation content as in the Roman baths and the Blur Building. In the above cases, three approaches to relating architecture and weather can be observed. Below, the term environment is used in order to connect to notions discussed hereafter.

Figure 3.4

Blur Building by Diller Scofidio + Renfro creating structure and environment from moisture control. Photo by Diller Scofidio Architects

(1) Construct of environment for architecture
This can be seen in the Roman baths, as weather constituents are used for the construction of a particular environment, which increases the legibility of the architectural intention.

(2) Construct of environment by architecture
This can be seen in the Nordic Pavilion, as weather is constructed through the interaction with architecture. It is, in this case, the composition of the construction that modifies the environmental conditions.

(3) Construct of architecture by environment
The reverse process of the one mentioned above, in which the components of weather are the basis for architectural articulation, as is shown in the Blur Building. The composition of weather creates the understanding of a defined space and its properties.

In all three cases, the agency of weather is a determinant of the phenomenological perception and practical functioning of the building in relation to the architectural intent, its performance. Obviously, (3) construct of architecture by environment only exists if weather is created, whereas the former two, (1) construct of environment for architecture and (2) construct of environment by architecture, remain physically present. Nevertheless, it can be suggested that the architectural identity and its relevance to humans rely entirely on its ability to create environments from weather constituents.

The above deductions from the examples align, therefore, with the notions of Hill, who underpins the reciprocity of weather and the construct of architecture beyond the understanding of weather being able to be divided from architecture or, even further, to act only as a passive engagement.

> *…Increasingly, architecture and weather are two interrelated elements of a complex system. Defining nature-culture relations, the term 'coproduction' applies to architecture as well as the weather. Just as the intermingling of natural and human forces creates contemporary climate and weather, a building results from the relations between nature and culture that arise during its conception, construction and use… (Hill, 2012:321)*

Architecture, as asserted by Hill and by the examples above, illustrates the capacity of weather to become the determining aspect in relation to constructing local specific and environmentally oriented architectures. The conceptual and physical separation between what is inside and outside in architecture, despite the use of walls or the lack thereof, becomes less important. This statement has an oppositional argument. British architectural historian Robin Evans argued in his influential essay *Rights of Retreat and the Rites of Exclusion: Towards the Definition of Wall* that the architectural partition has functionalities as a separating element in, for instance, prisons and monasteries (Evans, 1971). Under these conditions, the understanding of spatial boundaries remains intact. Evans argued that this enables the possibility not only for imprisonment, but also for a spiritual retreat. The perception of space, and its boundaries, may therefore be articulated by the intention to isolate connectivity to environmental context. This, however, as has been stated in the Introduction, is not having a positive effect on humans in general.

An articulation of architecture without a focus on the separation advocates another form of architectural description and understanding of what architecture elements are, beyond the mere obvious walls, floors, doors, et cetera. Such an orientation may be advanced by an increasing interest in phenomenological atmospheric conditions, as will be examined below.

Atmosphere

As mentioned above, atmosphere can have two meanings, one related to the macro climate conditions of the gases surrounding the Earth, the modifications of which have a direct impact on global warming (IPCC, 2014), and another meaning referring to the mood of a place and/or situation. In the world of environmentally sustainable architecture, both meanings are relevant. The former is affected by the collective workings of the built fabric as a whole, while the latter is related to the singular articulation of space as directly perceived by humans. Swiss architect and writer Peter Zumthor stated, when needing to describe how architectural beauty and natural presence come to be, *'one word for it is atmosphere'* (Zumthor, 2012:11).

Following the assumption of this thesis, that environmental architecture is a sustainable architecture, we will focus mainly on the second meaning of atmosphere as we discuss an environmentally oriented architecture.

The architects of the Blur Building have already introduced us to the notion of atmosphere in architecture, as they use the term as a fundamental aspect of building – *'The Blur Building is an architecture of atmosphere'*. This presents the first etymological challenge of atmosphere in architecture, as the meaning is moved from its position of being an immaterially defined concept (mood) to a physically perceived, measurable and identifiable, if also ephemeral, entity constituting the architectural makeup and its articulation. By extension, one might want to remember that atmosphere comes from Greek 'atmos' and 'sphaira', originally meaning 'vapour' and 'globe' (OED, 2014). This strengthens the application of the word to the usage by architects Diller Scofidio + Renfro in the Blur Building and its twofold capacity (meaning and function) in architecture.

In approaching atmosphere as an element of building, German philosopher Gernot Böhme points to the understanding of architecture and its locality not through the physical fabric of walls, roofs, et cetera, but through the notion of atmosphere perception. Böhme stated:

> *Our presence, where we are can also be topologically understood as a determination of place. Indeed, sensing physical presence clearly involves both physical distance from things, whether they are oppressively close or very remote, and also spatial geometry, in the sense of a suggestion of movement,*

> *reading upwards or bearing down. But a sense of 'whereness' is actually much more integrating and specific, referring, as it does, to the character of the space in which we find ourselves. We sense what kind of space surrounds us. We sense its atmosphere. (Böhme, 2005:402)*

Böhme's philosophical orientation is elaborated from the writings of German philosopher Martin Heidegger with the notions on mood, 'Stimmung' (Heidegger, 1973) and French philosopher Maurice Merleau-Ponty's writings on 'Phenomenology of Perception' (Merleau-Ponty, 1962).

Before defining the fundamental element of architecture as atmosphere, that is, the feeling in a given surroundings, Böhme points to why atmosphere is so central to architecture in repeating that architecture is perceived via many senses and therefore should surpass the visible as the singular orientation of architectural observation.

> *So, what does really count? If we briefly review the basic implications of the comparison with other arts – form and content, expression, meaning, harmony – the sculpture seems to be the closest to architecture. Don't the two fields, inasmuch as they both shape matter, work in the domain of the visible? – at which point the architect, by working for visibility and treating design as lending form to mass, has already succumbed to the seduction of the arts. But, then, is seeing really the truest means of perceiving architecture? Do we not feel it even more? And what does architecture actually shape – matter or should we say space? (Böhme, 2005:399)*

Böhme presents his thoughts from a philosophical standpoint but parallels closely the notions of Zumthor, who in his buildings, with particular attention given to the Pritzker price project of the thermal bath, Therme Vals (1996)[Fig.3.5], literally constructs what he writes, *'this singular density and mood, this feeling of presence, well-being, harmony, beauty...under whose spell I experience what I otherwise would not experience in precisely this way'* (Zumthor, 2012).

The bath in Vals, like the Roman baths mentioned above, is explicitly made to create an atmosphere of thermal experiences. It does so by radiation from the surfaces surrounding the occupier, heated and cooled air for convection effects in locations of non-direct connection to solid material, and immersive conduction of heat that is present as the body is lowered into water of different temperatures. Solids, fluids and gaseous conditions are coordinated to create versatile environmental experiences.

Finnish architect and theoretician Juhani Pallasmaa elaborated on the architectural potential of atmosphere in his book *The Eyes of the Skin – Architecture of the Senses* with rigorous opposition to the visible-oriented approach of contemporary architecture. From studies and sources in physiology, he posited:

> *All the senses, including vision, are extensions of the tactile sense; the senses are specialisations of skin tissue, and all sensory experiences are modes of touching, and thus related to tactility. Our contact with the world takes place at the boundary line of the self through specialised parts of our enveloping membrane. (Pallasmaa, 2012:12)*

Figure 3.5

Thermal Bath in Vals by Peter Zumthor (2009). Thermal environments are created from solid and fluid matter perceived under different specified environmental conditions. Photo by Jennie West.

By positioning the visible sense of atmosphere as an extension of the tactile body, the question of a hierarchy of atmospheric perception, where the visible is considered the most important, is instead translated to a network of senses to create a more nuanced understanding of a given environment.

Furthermore, this form of seeing or legibility is supported by neuroscientist Jeff Hawkins, who explains through his studies on intelligence (Hawkins & Blakeslee, 2004) that humans' ability to comprehend a given material's characteristics is based on the tactile reading by movement of the sensing organ against what is to be perceived. Hawkins uses the example of wood, which is detected as one moves a finger across its fibres, identifying its structure. If we only place the finger on the material without movement, the brain is not receiving information against the knowledge it already has to characterise and experience the material. This form of identification is applicable to all sensing and thus to the notion of atmospheric reading and perception.

Factually, Hawkins's studies explain the Pallasmaa's notions of *'the eyes of the skin'*, which again underline the workings of the Therme Vals project, in which the human extensively reads a designed atmosphere by the person's movement or by the movement of thermal convection, radiation and conduction processes.

Thus, relative movement is central to the perception of a given object and of a given environment. This understanding responds directly to the initial question (Q1) of how material and environmental dynamics are central aspects to environmentally oriented architecture and therefore to the theoretical framing of Environmental Tectonics. To support this argument, American architectural scholar Lisa Heschong wrote in her book *Thermal Delight in Architecture*:

> *As with all other senses, there seems to be a simple pleasure that comes with just using it, letting it provide us with bits of information about the world around, using it to explore and learn, or just to notice. (Heschong, 1979:18)*

And:

> *We can only smell a rose for so long before the smell fades away. The sensors become saturated and attention moves on to new information. Our nervous system is much more attuned to noticing change in the environment than to noticing steady states. (ibid:19)*

Atmosphere is, from these perspectives, created from perceiving climatic environments, in temporal and specified conditions, determined both by human activity, such as movement, and by environmental variations.

From observations of atmosphere as the primary articulation for architecture, Böhme mounts his theory of beauty and aesthetics (Böhme, 2010). In this, he repositions what classical aesthetics are based on by shifting the visual and proportional understanding of aesthetics to a sense-based understanding of an aesthetic dimension in architecture. This understanding of an aesthetic dimension and its implications for an Environmental Tectonic approach is further discussed in the chapter entitled *Correlations*. However, as the basis for further discussion of environmental human-oriented architecture in

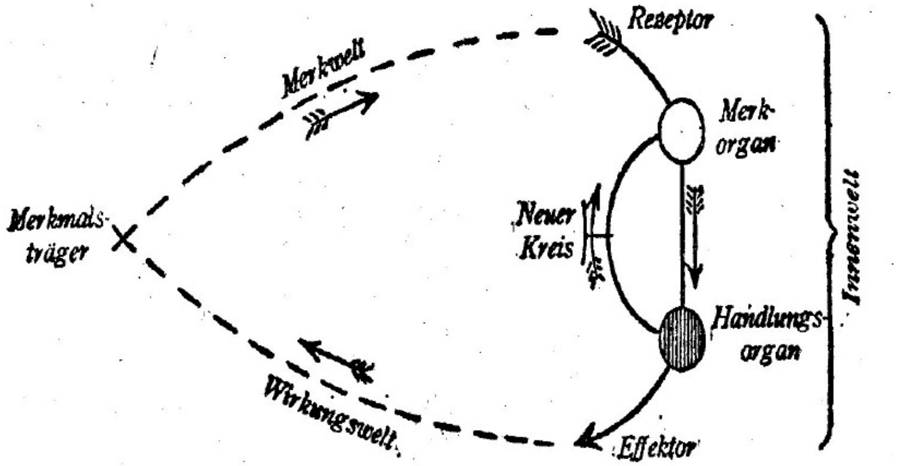


Figure 3.6

Uexküll's Funktionskreis (1920) illustrating the feedback process between an organism and its perceived environment. Drawing by John von Uexküll.

which aesthetics is constructed from atmosphere, and atmosphere is created from the articulation of architectural environments, the following question arises:

How are environments constructed with an orientation towards the making of environmentally sustainable aesthetic architectures?

This question parallels the underlining theoretical framework of Environmental Tectonics with the intention of formulating instrumental environmental architectural methods and models. Below, a closer examination of the construction of an environment is conducted.

Environment

To restate what was discussed above, environment has two meanings, *'the surroundings or conditions in which a person, animal or plant lives and operates'* and *'the natural world, as a whole or in a particular geographical area, especially as affected by human activity'* (Oxford Dictionary, 2014).

In specifying the terminology, Michael Hensel pointed us to an extended definition of environment from the field of ecology (Hensel, 2013:48), with the formulation of environment being the *'complex of biotic, climatic, edaphic (pertaining to, or influenced by, the nature of the soil) and other conditions, which comprise the immediate habitat of an organism; the physical, chemical and biological surroundings of an organism at any given time'* (Lincoln, Boxshall, & Clark, 1998:101).

Several key aspects of relevance are mentioned here. People, animal and plants are all connected through the environment, and they all influence the environment, underpinning a reciprocal relationship. This relationship is based on time-specific physical, chemical and biological processes, which construct the habitats for humans, animals and plants. The notion of environment in relation to architecture can therefore be aligned closely to the understanding of atmosphere, and it can be suggested that atmosphere could be the result of constructed environments in architecture.

In order for the construction of environments and therefore atmospheres to become more attainable, it is of benefit to look to the Estonian-German biologist Jacob von Uexküll, who was perhaps the first to explore the relationships that form an environment. Uexküll argued through the notion that each organism creates its own environment based on its actions and its abilities to perceive the surroundings. This has traces of the notion proposed by Hawkins, that is, the active movement of the finger to perceive. The fundamental principle underlining his *Umweltstheorie* from 1933 is the continuous feedback between two realms, the perceived world, *Merkwelt*, and the effected world, *Wirkwelt* [Fig. 3.6]. Through the correlation between these two realms in a functional cycle, *Funktionskreis*, an environment is created. Uexküll posited:

> *The object only takes part in this action to the extent that it must possess the necessary properties, which can serve on the one hand as feature carriers*

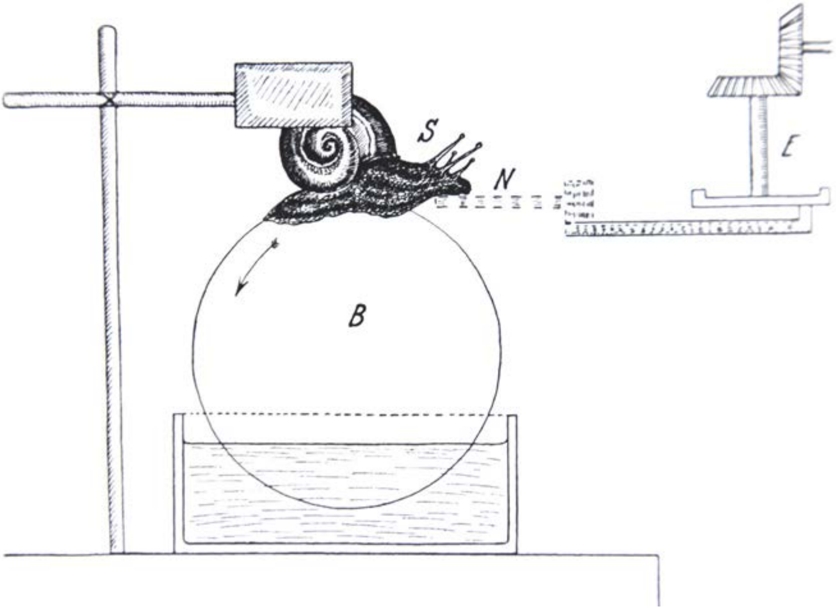


Figure 3.7

Uexküll'a snail experiment (1933) to determine the perception of an organisms environment by sensory registrations. Drawing by John von Uexküll.

and, on the other as effect sign carriers, and which must be in contact with each other through a reciprocal structure (Funktionskreis). (Uexküll, 2010 [1933]:49)

Here, Uexküll points to his classification of *Umwelt*, which is created by the aforementioned two realms connected by the Funktionskreis, and *Umgebung*, referring to the simple geographical environment, and lastly *Welt*, referring to the scientific universe. The depth of Uexküll's Umweltstheorie is more profound than perhaps initially thought, as Umwelt designates all the elements that come into play in the elaboration and perception of an environment. As asserted by George Canguilhem in his writings on milieu, referring back to Uexküll's work,

From the biological point of view, one must understand that between organism and environment there is the same relationship that exists between the parts and the whole within the organism itself. The individuality of the living does not come to an end at its ectodermal boundaries, no more than it begins at the level of the cell. The biological relationship between the being and its milieu is a functional one, and as a result it changes as the variables successively exchange roles. (Canguilhem, 2001:19)

This indicates the interactions and consequences, on multiple levels of operation, upon the construct of a perceived environment. As an example, provided by Uexküll (2010:79) in his studies of tactile sensory behaviour of animals, a snail is positioned on a rubber ball placed in a water basin, in such a way that the ball can rotate as the snail attempts to move in any direction, while being held in position by a clamp [Fig. 3.7]. A stick is then placed in front of the snails 'foot', which it intuitively will try to crawl onto. If the stick is moved from side to side with a frequency below three to four times per second, the snail will not attempt to crawl onto the stick. If the frequency increases to more than four times per second, the snail starts to crawl, indicating that the snail perceives the stick to be at rest. Uexküll concludes from this that the snail has a perception time of three to four times a second, meaning that all processes of movement take place much more quickly in the environment of the snail than in the perception of humans. Another example, based on seeing (ibid: 68), is the development of the farthest visible plane of humans, the farthest humans can see. As a human adult, this plane is situated approximately six to eight kilometres away, whereas an infant's plane is situated approximately ten metres away, where the muscles of the eyes are at rest. Only by gradually pushing the plane further away, by the help of distance signs, do humans expand their visual environment.

The articulation of an environment is thus not only based on the making of external attributes of the human, but extended as a relation to the perceiving and acting individual, who in a reciprocal process himself constructs the environment from individual sensory capacities. In addition, Uexküll stated from his studies that simple organisms construct simple environments, whereas complex organisms construct complex environments (ibid: 50), echoing the above descriptions of humans' potentially deep environmental perceptions through thermal stimuli and actions as intended in the Therme Vals project by Peter Zumthor. Using the points laid out above as a point of departure, the list of how humans potentially construct environments in architecture can be extended.

(4) Construct of environment by perception
This can be understood as the making of an environment based upon the sensory apparatus and sensory stimuli available to the organism. This indicates an orientation towards a stronger understanding of the specified human (occupier) and architecture capacities to intensify the reading and construction of an environment. Also, if the ability of sensing is projected onto buildings by sensory mechanisms like thermometers, infrared cameras and so on, a building's ability to sense as a basis for perception increases.

In support of Uexküll's theories, and to a further pathway for this thesis, Herbert Simon describes in the book *Science of the Artificial* how objects have an 'inner' and an 'outer' environment (Simon, 1996:6), with the former describing the working of the object at one side of a threshold and the latter at the other side of a threshold. The intentionally vague formulation of a given threshold is based on the dynamic positioning of what belongs to the inner environment and what belongs to the outer environment. Hence, environmental construction is more intricate in its definition by its temporal demarcation of the threshold under study. This may seem abstract, but it follows Canguilhem's notion in that the positioning of an environmental boundary is dynamic and not necessarily positioned at the outer surface of an object, which in Simon's extensive examples and writings can be found in everything from economic systems (ibid:25) to engineering design (ibid:111) and biological systems (ibid:183). Not only does this suggest that the understanding and articulation of environments in architecture can be nuanced, openly specified and dynamic in character, it also suggests that the construction of environments perceived by humans is, to a high degree, determined by the interface of both material and immaterial understanding of flux between multiple definitions of an inner and an outer environment. Thus, a construction of an environment based upon the above processes of perception and environmental thresholds situates an environment further towards the immaterial field, both in how to understand a given system and in its physical contexts. It necessitates, therefore, the physical processes inherently present in the physical world, Werkwelt, and the mental world, Wirkwelt, to use Uexküll's terminology.

Interestingly, another stratum to this orientation is provided by the American former natural scientist and now architectural scholar Michelle Addington, who, in her physics-oriented approach to architecture and its constructions, points out that a perception of environment is situated where *'we sense ourselves and only indirectly sense our environment'* (Addington, 2007:48). Thus, the architectural theories of Pallasmaa and the biological theories of Uexküll and others (Canguilhem, 2001; Uexküll, 2010) align with the neuroscientific theories of Hawkins et al. (Hawkins & Blakeslee, 2004) and the systems theory of Simon (Simon, 1996) in questions of environmental constructions.

The construction of architectural environments is hence both complex and dynamic in its manifestation. A further examination of the material and immaterial dimension is conducted below, with the intent to develop the theoretical path and to approach in closer proximity the overarching hypothesis and research question formulated in the Introduction to this dissertation.

3.2 Material

Returning to the etymology of material, it is formulated as *'the matter from which a thing is or can be made'* originating from the Latin word 'materia', also meaning matter (OED, 2014). Material, which architecture is constructed from, is in its meaning not bound to classic architectural descriptions of solid walls, floors, ceilings and doors, but to the more open notion of matter, from the Latin. Matter is commonly described by its physical properties, being in one of the three phase states of solid, fluid and gaseous, rather than its static material condition, which is used in architecture by describing a material as glass, stone, bricks, et cetera. Presumably, architecture, in its use of apparent material descriptions, disregards the actual materialisation taking place. By levelling a material and its processes into one representational description, the potential for 'true' architectural materialisation, and thus its articulation, is decreased. American architect and scholar Christopher Williams stated that:

> *Grasping the unity between these three states is often more revealing than defining their differences. The world as we know it is a whole and all its parts respond to the same earthly laws; all substance about us has the same physiochemical basis; all particles of matter are moulded by the same physical laws. The structural unity is time. (Williams, 1995:14)*

The threshold, marking an inner and outer environment, as described by Simon, may assist us in understanding how and at what level of operation the architect must work in order to construct architecture from a more inclusive and matter dynamics-based orientation, as is stated by Williams.

In spite of the physical laws and the factual conditions at work, this manner of thinking in architecture appears to be disregarded when building today, as buildings are increasingly constructed to operate in static and isolated conditions. This architectural agenda can be seen in the theoretical perspective of Evans when he argues for a spatial potential by isolation and an applied perspective in current energy-based approaches promoting isolation through insulation (Moe, 2014).

In contrast, by returning to the arguments and writings of Jonathan Hill, clearly arguing for architecture and weather coexistence, material is described as a somewhat isolated, auxiliary and autonomous entity.

Moholy-Nagy agrees that space does not have an independent existence; a definition of space which may at least be taken as a point of departure is found in physics – '*space is the relation between the position of bodies*'. But these bodies are

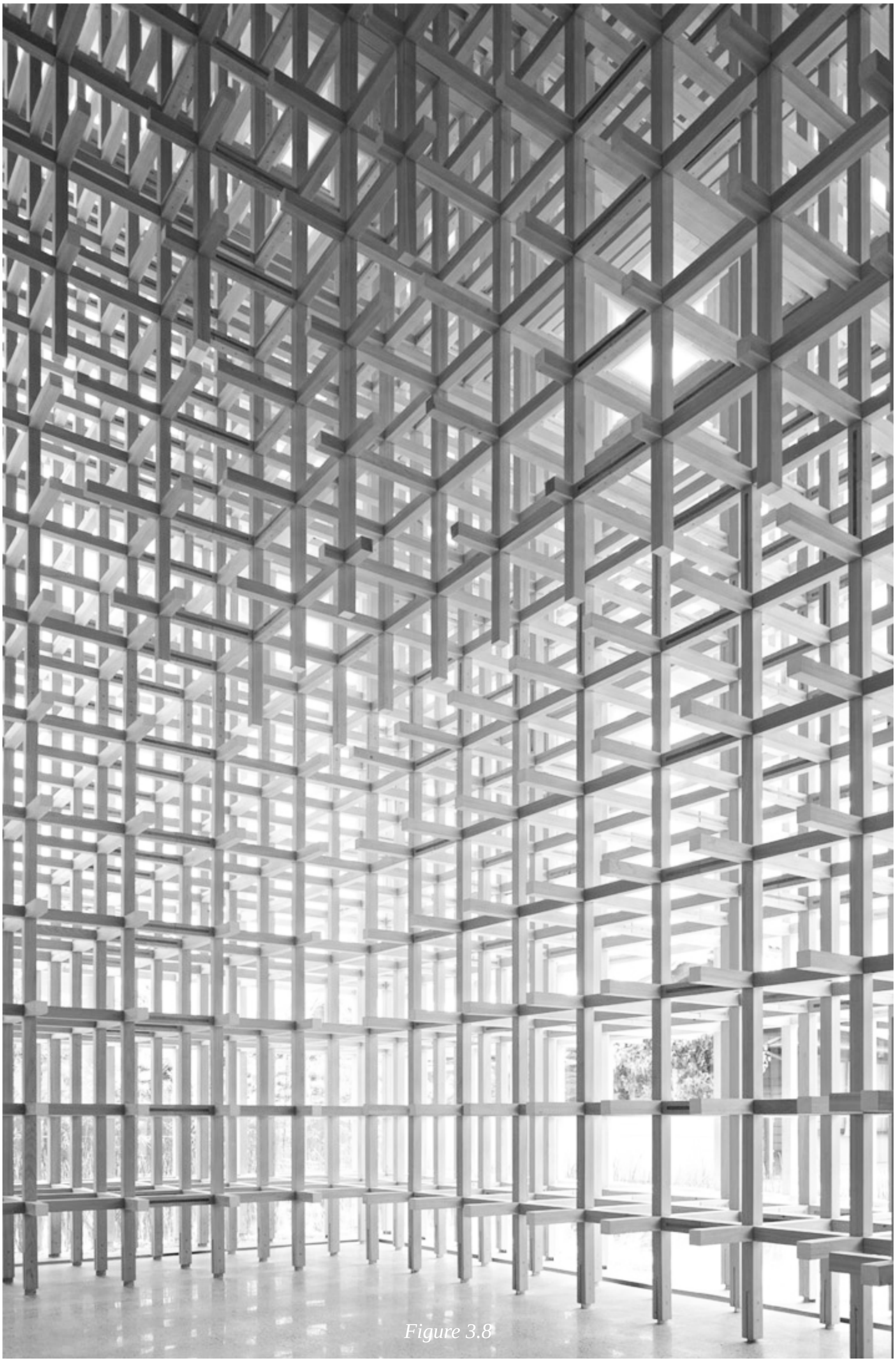


Figure 3.8

GC Prostho Museum in Hida Takayama (2010) by Kengo Kuma illustrating the architect's work with particalizations through numerous elements. Photographer unknown.

mere necessity, his principal concern is the relation between spaces: *'Space creation becomes the nexus of spatial entities, not building materials. Building material is an auxiliary, just so far can it be used as a medium of space-creating relations.'* (Hill, 2006:67)

Conceptually, however, Hill proposes the elusive space description as a constellation of forces and relations that are immaterial, which partially adheres to the more evocative statement of Williams.

> *'Moholy-Nagy describes space as "this material" and writes that the phrase "materials is energy" will have significance for architecture by emphasizing relation, instead of mass. The recognition that matter is energy focuses attention on space as a kinetic force-field of fluid relations and minimal substance, he contends. Space is the material of immaterial architecture.' (Hill, 2006:67)*

Equalling matter with energy surpasses the notion of architecture as the composition of static solids. Architecture, from this perspective, is thus comprehended as the organisation of matter-dynamic relations, where an architectural description is much more fluid and interchangeable. The reciprocity of an architecture that is more a synchronisation and exchange of elements, rather than autonomous entities, becomes clear in the words of American architectural theoretician Sanford Kwinter, as he posited:

> *What is central here is the dynamical theory of morphogenesis, which characterizes all forms as the irruption of a discontinuity, not on the system but in it or of it. For a form to emerge, the entire space (system) must be transformed along with it. (Kwinter & Boccioni, 1992:58)*

Such a formulation relates directly to the philosophical thinking influenced by the French philosopher and Nobel Prize Laureate Henri Bergson, who described transformational processes by matter and evolution (Bergson, 1911). The philosophical grounding of matter and its transformative properties in relation to architecture have also been stated by philosopher of science Manuel DeLanda, who points to French philosopher Gilles Deleuze's writings on matter processes when taking form into objects (DeLanda, 2004).

Applied to architectural practice, Japanese architect Kengo Kuma introduces the term 'particalization' (Frampton, 2012:18; Kuma, 2012) with the aim of describing how he evokes architecture. Kuma stated:

> *We are composed of matter and live in the midst of matter. Our objective should not be to renounce matter, but to search for a form of matter other than objects. What that form is called – architecture, gardens, technology – is not important. (Kuma, 2012)*

By this statement, Kuma supposedly grasps and promotes the physical, architectural and philosophical notions above. However, on closer reading, the organisation

Figure 3.9

Media-TIC building in Barcelona by the architectural office Cloud9. The building illustrates how gaseous material can be used as a thermal structure that define the envelope. Photo by Isak Worre Foged.

or composition of matter is often conceptual [Fig. 3.8], rather than physical. In a description of one of his projects, Kuma writes:

> *…When looking out at the Pacific Ocean, I too felt that water was not a static volume, but a series of continually changing particles, and that the building I was designing, which overlooked the ocean, also ought to be a collection of sparkling particles. Here, I used aluminium louvres for the first time, because I wanted water to impart to the building the particle-like character of the sea via the brilliance of those louvres. I discovered through this project that when nature exists as particles, a building that stands within it must itself be composed of particles. (Kuma, 2012:28)*

While Kuma's formulation of matter is aligned with some of the theoretical notions above, it appears just as metaphorical as it is physical and operational in its approach to an environmentally sustainable architecture. The aforementioned Blur Building, on the other hand, indicates a much more explicit and non-decomposable construct, with no separation in what constitutes the building and what constitutes the environment. In keeping with the dynamic threshold of an environmental boundary, the Blur Building constructs this boundary from as far away as the cloud is constructed, dynamically depending on the cloud created, to as close as inside the human body.

A recent example illustrating the use of confined matter for environmental modulation is the Media-TIC building (2010) in Barcelona [Fig. 3.9], constructed by the Spanish architectural office Cloud9. On the southwest-facing façade, large ethylene tetrafluoroethylene (ETFE) cushions are placed. These can be filled with nitrogen and oil (Burry, Giralt-Miracle, & Rifkin, 2010) changing the otherwise semi-transparent envelope to an opaque vertical cloud. The non-mechanical adjustments of light and thermal control is based on the mixture between clear air and nitrogen oil composition. In contrast to the geometrically complex, free-form Blur Building, the Media-TIC is a strict platonic geometry, a rectangle, approaching the dimensions of a cube. Not only is the matter (air, nitrogen and oil) confined in space within the cushions, it is also withheld from direct contact with humans. In this regard, it is much less immersive as an environmental architecture compared to both the Roman baths and the Blur Building.

Thus, it can be suggested that the Media-TIC building applies the same strategy as the Blur Building, but in a less invasive manner and in confined spaces, prevented from unintended mixing between the building cushion's inner and outer environments, separated by the ETFE membrane film. From this, the Roman baths and the Media-TIC construct 'bounded matter organisations' applying environment to modulate environment; the difference is in the positioning of the environmental boundary, as perceived by the human.

This identifies a contradiction, as 'bounded' matter organisation inherently suggests an enclosure, a separation, which is in opposition to the idea of open environmental constructions.

Figure 3.10

Royal Theatre Copenhagen (2008) by Architects Lundgaard & Tranberg and Engineering Firm COWI. The large glass canopy is thermally conditioned by energy from the harbaour water. Photo by Isak Worre Foged.

Thus, it provokes the question:

Can bounded matter organisation be organised to interact with its outer environment?

To pursue this question, we must focus on how matter in architecture is organised and informed by energy systems, allowing the transfer and organisation of both bounded and open matter organisations.

3.3 Energy

In the last section it was shown how matter could be understood as a building material, how it can be organised to modulate environments, but also how it may construct deep sensorial effects on humans, and thereby possess the ability to construct atmospheres and profound architectural aesthetic articulation. The identification of open and bounded organisations of matter orients the focus on how environmental aspects remain interconnected, despite a form of constrained construct.

Within the Royal Theatre in Copenhagen (2008)[Fig. 3.10], created by Danish architects Lundgaard & Tranberg and Danish engineering firm COWI, large pipes filled with fresh water connect the thermal energy situated in harbour water with the building. By moving water from the harbour into the building, the building is cooled or warmed, depending on the temperature differences between the two and the intended thermal environment inside. Water is not in direct (conductive) connection with the human body, as in the cases above, rather, it immerses the building structure profoundly. Water, in this way, becomes the predominant material make-up, which modulates the internal environment for humans. Interestingly, water within the building is specifically guided to the upper level with the large glass canopy, creating a complex deep spatial building membrane. Theatre actresses and actors have their personal champers in these spaces, positioned at the interchange between energy flows from the sky and the adjacent Copenhagen Canal. The extension of thermal environmental modulation is here extended to a non-visible and dynamic boundary within the water, dissolving the notion of a static boundary enclosure, yet organised in the duality of bounded and unbounded flows of matter. The specificity of thermal spatial regulation is thereby available to the most important occupiers of the house, as they receive direct thermal sensations through two methods of radiation, by the sun and by the surface, that are much more fluid and dynamic in their construction than what they appear to be from a purely visible perspective. The complexity of the environment and the definition of aesthetics are thereby constructed by this multi-layered sensorial perception. The organisation of matter is also the organisation of energy. However, this articulation is not readable in the design, making it unclear how and why the architecture constructs a positive aesthetic dimension based on the dynamic organisation of matter and energy. In this manner, the Royal Theatre presents a third level of matter organisation by withdrawing the material-environmental further away from the human perceiver, nevertheless illustrating how a dynamic exchange can be both open and confined to its surrounding climate and to the occupiers of the building.

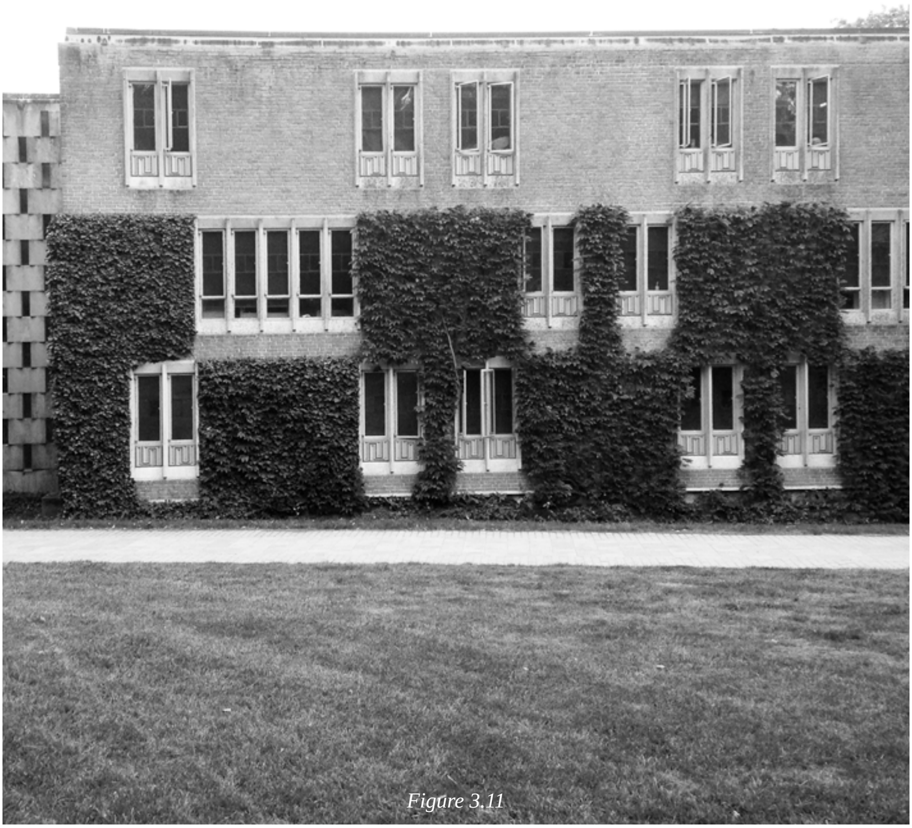


Figure 3.11

Vegetative membrane on a building at the Princeton University Campus. Photo by Isak Worre Foged

It can be suggested that the building makes use of the available energy in its context and uses matter to organise its human-perceived thermal environments. In engineering and physics, this way of obtaining available energy in a system is referred to as 'Exergy' (Yantovski, 2004:6). This leads to the general definition, '*Exergy is the maximal work, attainable in given reference state without generalized friction. In the closed system energy is conserved but exergy is destroyed due to generalized friction'* (ibid). Hence, in a closed system, as defined by physics, the ability for energy to do work is decreasing, whereas in an interconnected and open system, the basis for harvesting energy is created. The above example, Royal Theatre, does exactly this, as it makes use of the flux of energy in an open system (sun and sea), maintaining a high level of exergy to be employed by architecture as a means to articulate thermal environments. This shifts the predominant focus of sustainable architecture in general, from the idea of using less energy to an idea of simply organising the energy more intelligently. In the words of American architectural scholar Kiel Moe:

> *In contrast to the conservation paradigm, the aim for architects should shift from using less energy toward the means of capturing, channelling, and producing energy available in the milieu of a project. (Moe, 2007)*

Developments of energy systems in architecture, which employ the measure of exergy over energy, are predominantly occurring in the development of technical systems, such as heat pumps (Meggers & Leibundgut, 2011; Meggers, Ritter, Goffin, Baetschmann, & Leibundgut, 2012). These advances in engineering of mechanical constructs have, however, led to an increase in the application of such machinery in architecture, but it has also increased the knowledge of energy flows in systems and how to utilise energy in more innovative ways in architecture. While the quantitative measure of 'energy efficiency' remains the prevailing basis for sustainable architecture, as mentioned in the Introduction, the qualitative measure of 'exergy' may be a more beneficial focus as we seek to move towards a sustainable architecture based on the organisation of matter as environmental constructions.

Perhaps the most advanced thermal modulation system imaginable in architecture, in which matter is continuously organised to maximise exergy, is the vegetative membrane [Fig. 3.11]. Employing solar energy, soil energy and water energy to construct itself, a vegetative layer makes use of multiple sustainable environmental sources to maintain and develop. In this process it regulates its own microclimate to evolve and interact with the nearby thermal environment by well-known processes of filtering sunlight, absorbing and releasing moisture, reducing carbon dioxide and producing oxygen.

American scientist T.R. Oke elaborated in his book *Boundary Layer Climates* on the properties of the organisation of matter and energy in a vegetative layer. Here, it is clear that the processes taking place are multifaceted time-based interactions occurring at different locations in the leaf layer organisation. However, the required condition that the matter organisation remains both porous and enclosed by its internal structure, in response to the climatic variations and the position of a human, increases the complexity of describing and utilising such matter organisation processes in architecture.

Oke posited:

> *Problems arise in determining the position of the surface in many natural environments… For climatic purposes we define the 'active' surface as the principal plane of climatic activity in a system. (Oke, 1987)*

Thus, Oke underpins prior notions by describing the factual physical condition of a more complex and three-dimensional organisation and reading of boundaries between what is visible and what is not, understood as inner and outer conditions.

A deep leaf layer acts, similarly to the Blur Building, by its complex capacities to regulate an environment. In addition, it is self-regulating and confined, both by its own processes of growth and by the potential human agency of pruning and seeding.

Recent studies to understand the properties of vegetative building layers have been studied from an engineering perspective with the objective of identifying the thermal insulation properties when located as an auxiliary membrane in an existing building structure. These studies reveal a dynamic capacity to level thermal peaks across night and day, summer and winter (Susorova, Angulo, Bahrami, & Stephens, 2013; Tilley, Price, Matt, & Marrow, 2012).

The particular properties of some vegetative membranes to expand and contract its surface layers are significant. By allowing the leaves to fall off and be regenerated within an annual cycle, a radical modification of its appearance and abilities to modify local thermal environments is embedded. Nevertheless, what these studies do not examine is the dynamic expansion and contraction across the building surface over an annual period and the effect of their colouration. Nor do they examine the ways in which the dynamic growth enables an extended reading of an environmental context. Both aspects seem relevant to architecture and to the application and exemplification of matter-based architectural constructs.

In this section, it has been shown how energy, or rather exergy, can be used through the organisation of matter towards the construct of a specific environment and atmospheres. A potential extension to aesthetic articulations has also been included, which will be elaborated upon in the following chapters. Two examples have been shown that exhibit bounded matter organisations, which dynamically exchange and aid the construct of thermal environments for humans. These examples identify an opposition and another agenda for sustainable architecture other than the current predominant approach of separation between a so-called inner and outer environmental condition. However, the examples also ally with the principles of Free-Running Buildings based on vernacular architectures. The principal difference is that this approach focuses on the construction of environments geared towards sustainability, whereas FRB modifies the notion of thermal comfort through human adaptation enabling a reduced difference between the external temperature and that desired by humans. This is an important distinction, as the construction of environments is a prescriptive approach to increase thermal environmental articulations towards both energy-sustainable and aesthetic architectures.

These arguments address directly the question at the outset of this chapter, initially formulated within the Introduction chapter. In developing an instrumentation of this theoretical orientation towards environmentally sustainable architecture, the section below attempts to adopt and adapt assessment methods, which in later chapters can be paired with tectonic and computational methods for an Environmental Tectonic approach.

3.4 Modelling Environments

In the previous sections, it was exemplified how matter and energy can be organised based on the exergetic capacities present within the climatic context, and how these can be used within deep, complex membranes, where environmental boundaries are difficult to define stringently, from both visible and non-visible perspectives. In addition, it was shown that these can be organised by positioning of matter. To approach the way these organisations can be explicitly interlinked with human environmental sensation, this chapter examines and adopts methods for human environmental perception and attempts to illustrate how these can become instrumental in the work ahead towards implementation in early design phases. As American architectural theorist Lance Hosey stated:

> *How our bodies interact with the world has everything to do with how we view and treat the environment. Understanding the mechanics of this interaction better is essential to sustainable design. (Hosey, 2012:57)*

To make such organisations and mechanisms operational as instruments in architectural methodologies, it was asked:

How can analytical and numerical methods of human sensations of the environment be integrated into the architectural conceptual design phase? (Q4)

Acoustic

In terms of the audible perceived environment, architecture may be more active and interchanging as a basis for environmental understanding than is commonly understood. This has been acknowledged in the aforementioned European Standard, EN15251. Prior to this inclusion in governmental codes, the Danish architectural theoretician Steen-Eiler Rasmussen posited in his book *Experiencing Architecture*:

> *Can architecture be heard? Most people would probably say that as architecture does not produce sound, it cannot be heard. But neither does it radiate light and yet it can be seen. We see light it reflects and thereby gain an impression of form and material. In the same way we hear the sounds it reflects and they, too, give us an impression of form and material. (Rasmussen, 1964:224)*

Rasmussen parallels light and acoustics in the way they may be emphasised or modulated by architecture. Through engineering and physics, the measurements of architectural acoustics were advanced by the physical experiments of American physicist Wallace Clement Sabine, who by studies of concert halls found relationships between the volume of the space and the way the materials absorb sound waves (Long, 2014). What Sabine offers in his equation below is an impression of form and material as stated by Rasmussen, but expressed in numerical description. The acoustic description, still central today, is the time a sound level takes to decay with sixty decibels, known as the reverberation time, noted T_{60}. This measurement gives an impression of the ability of a space and its materialisation to be qualitatively described as, for instance, a live or dead acoustic environment. The Sabine equation:

$$T_{60} = 0.161 \frac{V}{A_t} \tag{3.1}$$

where T_{60} = reverberation time, V = acoustic space volume, and A_t = absorption coefficient of the material used.

For a material, homogenous and geometrically simple space with a low absorption, the Sabine equation remains the preferred method applied (ibid:331). In the case of more complex spatial-matter organisations, the average absorption coefficient can be difficult to predict, as each matter surface influences the At. For this reason the Millington-Sette equation, which is the method of including multiple absorption properties, is used:

$$S_T \bar{\alpha} = \sum_{i=1}^{n} S_i \alpha_i \tag{3.2}$$

where $S_T\alpha$ = summation of absorption properties of the surfaces defining the space, S_i = surfaces, and α_i = absorption coefficients.

This description has been inserted into the Eyring equation initially based on the Sabine equations, leading to the expression below for a low absorption, multi-material acoustic assessment. The Eyring equation:

$$T_{60} = \frac{0.161V}{-S_T \ln\left[1 - \sum(S_i \alpha_i / S_T)\right]} \tag{3.3}$$

So far, audible sensation is based on the reciprocity between the dynamics of the sound and the realisation of architecture. In addition, the spatial position of the perceiver adds to the perception, thus stressing the immaterial aspect of the construct of environments, suggesting an environment from both categories of environmental construction by architecture and perception. For such aspects to be applied to an architectural methodology, computational methods of ray-tracing sound paths can be applied. This leads to the combination of sound sensation assessments, or hybrid models extending the measurement with ray-tracing methods. From this, the matter field can be saturated with acoustic information, allowing an architectural representation to transfer non-visible phenomena for visible reading in early design processes. By ray-tracing, sound pressure can be defined by the equations:

$$L_p = 20 \log_{10} \left(\frac{p_{rms}}{p_0} \right) \qquad (3.4)$$

With L_p = sound pressure (dB). With p_{rms} = the root mean square of the sound pressure (Pa) and p_0 = the reference sound pressure (Pa).

$$L_{p2} = L_{p1} + 20 \log_{10} \left(\frac{r_1}{r_2} \right) \qquad (3.5)$$

With L_{p1} = sound level at distance r_1, sound level L_{p2} is from distance r_2.

The engineering equations offer a direct link to architectural environmental articulation by expressing the reciprocal relations between sound sensation via the description of spatial volume, spatial geometry, material and surface characteristics of scattering, absorption and reflection. Peter Zumthor points to the evident condition that sound sensation is present, whether articulated or simply existing on the basis of spatial-material relations. Zumthor posited:

> *Listen! Interiors are like large instruments, collecting sound, amplifying it, transmitting it elsewhere. (Zumthor, 2012:29)*

Thermal

In 1970, the Danish engineer and scientist Ole Fanger published his seminal work *Thermal Comfort* (Fanger, 1970a), which included a series of experiments registering the heat balance of humans under different thermal indoor conditions. These conditions were classified into several quantitative mathematical descriptions and a qualitative descriptive taxonomy (Fanger, 1973) using numbers and terms like ‘cold’, ‘cool’, ‘slightly cool’, ‘neutral’, ‘slightly warm’, ‘warm’ and ‘hot’. The application of one of the terms is related to how a human would perceive a thermal environment, being for instance cold or slightly warm. Fanger established six main aspects, which determine whether a person is in heat balance or not. These include two factors relating to human behaviour, ‘clothing rate’ and ‘metabolic rate’, effectively linked to a person’s clothing and physical activity level. Also included are four environmental factors, ‘air temperature’, ‘radiant temperature’, ‘relative humidity’ and ‘air velocity’. The correlation of these factors, based on Fanger’s thermal sensations equations, output

Figure 3.12

Sunbathing Russians near the wall of the Peter Paul fortress in Sct. Petersburg (March 16, 2009). While the air temperature is cold enough to maintain ice on the ground, the radiant temperature from the sun and the stone wall is high enough to stay outside without clothing. Photo by Elena Palm.

a series of values, including comfort temperature, operative temperature, predicted mean vote (PMV) and the predicted percentage dissatisfied (PPD) of a group of people under a given thermal condition in relation to a heat balance standard for humans in which they experience comfort. Fanger's model, including the six fundamental aspects, remains today, and is still considered state-of-the-art and implemented in all standards of thermal sensation and comfort forty-five years after their first implementation (van Hoof, 2008). Nevertheless, several adjustments and additions have been made to extend the equations to include a vast set of factors, from human posture and human position in a space to what temperature the food is when it is consumed. The depth of the equations increases with new findings on, for instance, respiratory processes affecting the cooling behaviour of the human body in relation to the effect of radiant energy on the dynamically calculated clothing surface and perceived skin temperature (Höppe, 1993; Maria La Gennusa, Nucara, Pietrafesa, & Rizzo, 2007; Susorova et al., 2013).

The ability of the original work to absorb more than forty years of modifications indicates the robustness and both theoretical and applied capacity of the model as an instrument to assess thermal sensation for humans. Particularly significant, and equally so for analytical engineering processes and architectural design methods, is the integration of both environmental and human factors in the determination of thermal sensation by the individual.

While the complexity of environmental construction by perception, as suggested by Uexküll and others, naturally includes a vast set of inputs not included in the Fanger model and its extensions, an instrumental description of physical activity and clothing rate points to a specificity of the individual perception and relation to a given environment.

Evidently, clothing behaviour is influenced by cultural and thermal causes, as can be seen in a stereotypical use of full suits for males in overheated offices and summer dresses for females in cooled shops and the like. In a similar manner, the metabolic rate is determined by thermal and non-thermal issues, as an insufficiently dressed person, to keep warm, will move himself into the radiant energy of the sun and towards areas of less wind, if possible. The movement into a favourable thermal environment or the increase of physical activity to generate heat are well-established behavioural patterns of humans.

These patterns of thermal regulation have been studied in terms of describing an alternative method for thermal comfort. As shown by Nicol and Humphrey when studying Free-Running Buildings (Nicol and Humphreys, 2002) humans' ability to modify their local climatic context with clothing, posture and activity have a significant effect on the perception of thermal comfort. Instead of the extensive descriptions of the Fanger methodology, Nicol and Humphrey offer a simpler assessment method, an adaptive thermal model, in which comfort temperature is a function of the external temperature. The adaptive thermal model equation:

$$T_c = 13.5 + 0.54 \cdot T_o \tag{3.6}$$

where T_c = comfort temperature and T_o = outside temperature.

This method has been shown to work in Free-Running Buildings within the external temperature span of 10-30 degrees Celsius. For other conditions, the complexity of factors at work to determine thermal comfort is necessary to understand. It is, for instance, rare to observe office workers increasing body temperature by running around in a cold bank office, as this is culturally unacceptable. While the adaptive comfort assessment method is attractive due to its simplicity, it reduces the ability to describe the thermal potential of architecture, as it is determined solely by human activity and the external climate.

Furthermore, Fanger's methodology of assessment of thermal sensation aligns with the notions provided by Addington, stating that we sense the skin before we sense the environment. This provides a more inclusive and instrumental methodology in relation to architecture, as it integrates the double effects of environmental attributes, as seen in the Blur Building (air temperature, radiant temperature, air velocity, relative humidity), with the perceptive effects of human behaviour as described above.

The instrumentality of thermal environmental construction is thus linked to the ability to articulate the six primary aspects of thermal sensation by observing architecture, weather and the human perceiver. Thus, in moving towards an increased perception of environmental articulation for humans, an essential element is an intensified emphasis on the construct of the human envelope as a primary location for environmental understanding.

Oke explains how the boundary layer of the human is affected by human behaviour and physiological reflex mechanisms that deepen the complexity of environmental thermal perception (Oke, 1987:218). This can be seen in the example of how body hairs automatically rise from the skin surface, thereby changing the properties of the body envelope by increasing the surface roughness layer, changing the laminar flow and thus decreasing the ventilation of the skin and the removal of heat from the surface (ibid: 221). Hence, the principle mode of thermoregulation adheres to different scales and inserts another aspect of environmental construction that is induced by the unconscious mechanism of the human.

Despite the physics-based formulations of the Fanger equations, Addington criticises (Addington, 2009:14) the outcome of the comfort equations for their generalisation in describing a common estimate of thermal comfort for humans by the aforementioned measure of Predicted Mean Vote (PMV). What she seemingly omits to consider, in the path to suggesting a generalised number for thermal comfort (PMV and PPD), is the large set of other values, which are intrinsically connected to the construction and articulation of architectural perceived environments. To explicitly approach the assessment and integration of factors that may be instrumental in architecture, Fanger's equations (Fanger, 1970b), as implemented into the current ISO 7730 standard (ISO, 2005) and adopted by several current research studies (Khamporn & Chaiyapinunt, 2013; M. La Gennusa, Nucara, Pietrafesa, Rizzo, & Scaccianoce, 2008), are explicated. The number describing the Predicted Mean Vote is found in the expression below:

$$PMV = \left(0.303e^{-0.036 \cdot M} + 0.028\right) \cdot \begin{bmatrix} M\left(1-\eta\right) - 3.05 \times 10^{-3} \cdot \left(5733 - 6.99 \cdot M\left(1 - \eta\right) - Pa\right) \\ -0.42 \cdot \left(M\left(1-\eta\right) - 58.15\right) - 1.7 \times 10^{-5} \cdot M \cdot \left(5867 - Pa\right) \\ -0.0014 \cdot M \cdot \left(34 - Ta\right) - 3.96 \times 10^{-8} \cdot fcl \cdot \left(Tmrt + 273\right)^4 \\ -\left(Tmrt + 273\right)^4 - fcl \cdot hc\left(Tcl - Ta\right) \end{bmatrix}$$

where M = metabolic rate per unit body (W/m^2), P_a = vapour partial pressure (*Pa*), *fcl* = clothing area factor, T_{mrt} = mean radiant temperature (C), T_a = air temperature (C), T_{cl} = clothing surface temperature (C), h_c = convective heat transfer coefficient (W/(m^2-K)), n = mechanical efficiency.

The general derived expression proposes the percentage dissatisfied, Predicted Percentage Dissatisfied, in a given environment. Obviously, measured against a standard comfort value, the intent is to generally arrive at a minimum dissatisfied number of people.

$$PPD = 100 - 95 \cdot e^{-(0.03353 \cdot PMV^4 + 0.2179 \cdot PMV^2)} \tag{3.8}$$

In order to calculate the equation above, clothing aspects need to be computed, based on the convective heat transfer and the clothing area factor. From this, clothing surface temperature is calculated based on the following expressions:

$$T_{cl} = 35.7 - 0.028M\left(1 - \eta\right) - I_{cl}\left\{3.96 \times 10^{-8} \cdot f_{cl} \cdot \left[\left(T_{cl} + 273\right)^4 - \left(T_{mrt} + 273\right)^4\right] + f_{cl} \cdot h_c \cdot \left(T_{cl} - T_a\right)\right\}$$

Where v_{ar} = relative air velocity (m/s), I_{cl} = clothing insulation ((m^2-K/W)). It should be noticed that the air velocity is relative, based on both environmental air movement and movement by the human.

The convective heat transfer coefficient is calculated using the expressions below, which need to be computed based on the conditional statement expressed within the equations:

$$h_c = \left\{ \begin{array}{ll} 2.38\left(T_{cl} + T_a\right)^{0.25} & for\ 2.38\,(T_{cl} - T_a)^{0.25} \rangle\ 12.1\sqrt{v_{ar}} \\ \hline 12.1\sqrt{v_{ar}} & for\ 2.38\,(T_{cl} - T_a)^{0.25} \langle\ 12.1\sqrt{v_{ar}} \end{array} \right\} \tag{3.10}$$

Additionally, the clothing area factor needs to be computed based on similar conditional statements:

$$f_{cl} = \left\{ \frac{1.00 + 1.290 I_{cl} \quad for\ I_{cl} \leq 0.078\left(m^2 - K\right)/W}{1.05 + 0.645 I_{cl} \quad for\ I_{cl} \rangle\ 0.078\ (m^2 - K)/W} \right\} \tag{3.11}$$

The mean radiant temperature (mrt) in glazed (transparent) constructs is significantly modified due to the change of surface radiant temperature differences and the direct radiation from the solar beam. Depending on design, the mean radiant temperature is calculated with an inclusion of the solar radiant energy. Various calculation methods have been developed based on the complexity of the design, and by resolution desired by the simulationist. In this work, the methods proposed by Gennusa et al (Maria La Gennusa et al., 2007; Maria La Gennusa, Nucara, Rizzo, & Scaccianoce, 2005) and Khamporn et al (Khamporn & Chaiyapinunt, 2013) are expressed below.

The contribution of the mean radiant temperatures from opaque surfaces can found by the expressions:

$$T_{mrt} = \left[\left(t_{s1} + 273\right)^4 \cdot F_{p-1} + \left(t_{s2} + 273\right)^4 \cdot F_{p-2} + ... + (t_{sn} + 273)^4 \cdot F_{p-n}\right]^{0.25} - 273 \tag{3.12}$$

And the mean radiant temperature, including solar energy contribution, is expressed with the extensions below:

$$T_{smrt} = \left[\left(T_{mrt} + 273\right)^4 + \frac{a_p}{\varepsilon_p \sigma}\left(F_{p-win}\, I_{trdiff} + f_p\, I_{trdir}\right)\right]^{0.25} - 273 \tag{3.13}$$

where T_{mrt} = mean radiant temperature due to surface temperature (C), T_{smrt} = mean radiant temperature due to surface temperature and solar radiation (C), *tsj* = surface temperature of the enclosure wall number *j* (C), *Fp-i* = angle factor between the person and surface *i*, $F_{p\text{-}win}$ = angle factor between the person and the glass window surface (= 0.312 when distance between the person and glass window is 0.2m), f_p = projected area factor, *ap* = absorptance of the outer surface of the person (standard value 0.6); *Ep* = emittance of the outer surface of the person (standard value = 0.97), *Rho* = Stefan Boltzmann constant (W/(m^2-K4)), I_{trdir} = transmitted direct solar radiation striking on the person (W/m^2), I_{trdiff} = transmitted diffuse solar radiation striking on the person (W/m2).

Also of importance is the angle factor determining the relation between the radiant surface and the person, expressed below, which helps determine the impact of radiant surfaces by geometric relations:

$$F_{p-i} = \left(\sum_{i}^{n} F_{p-i} = 1\right) \tag{3.14}$$

The transmitted direct solar radiation is calculated by the expression:

$$I_{trdir} = I_{dir} \cdot T(\theta) \tag{3.15}$$

Where I_{trdir} = direct solar radiation transmitted through the glass window (W/m2), I_{dir} = measured direct solar radiation incident on the outside glass window (W/m2), $T(\theta)$ = glass transmittance, which is dependent on the incident angle.

$$I_{trdiff} = I_{diff} \cdot T_{diff} \tag{3.16}$$

Where I_{trdiff} = diffuse solar radiation that is transmitted through the glass window (W/m2), I_{diff} = measured diffuse solar radiation incident on the outside glass window surface (W/m2), T_{diff} = glass diffuse transmittance.

It has already been indicated how the organisation of matter and energy in architecture can inform and modify the radiant conditions, as shown by the example of the Royal Theatre and by the brief notes on vegetative membranes and the wall at the Peter Paul fortress. The effect of such architectural techniques strongly influences the mean radiant temperature, and thus the ability to instrumentalise such methods in the conceptualisation and realisation of human-oriented environmentally architecture. Hence, multiple architectural factors relating to human aspects and environmental aspects are present within the equations. Besides the general factors of PMV and PPD, a set of temperature variants can be found, which, as has been shown in previous sections, have capacities to construct environmental sensations as an architectural articulation, rather than the mere search for a theoretical comfort, in the words of Addington.

While the conventional architectural and engineering approaches attempt to approximate solutions towards a theoretical comfort, the above numerical methods may just as well be applied to exploratory architectural work, which, given the richness of thermal sensation outputs, allows the organisations of matter to be paired with the perception and articulation of environments by novel architectural intent.

If, however, one is adopting the PMV as a scale in architecture, it is remarkable that as little as a few degrees' difference can offset the human physiological state from heat balance to being too cold or too warm and thermally dissatisfied. Lisa Heschong offers an elaboration on the effect of only slight temperature variations, echoing the provisions on climate by the IPCC as mentioned in the Introduction,

> *Life exists within a small range of temperatures. It comes to a standstill as water freezes and even the hardiest of bacteria are destroyed in boiling water. Each species of plant or animal has definite limits within which it can survive and even narrower range of temperatures where it can successfully compete with other animals. Ecologists have discovered that as little as a 2 degree Fahrenheit change in the average temperature of a lake will shift the dominant*

> *fish population from bass to catfish as one species becomes more efficient that the other. Thus, not only extremes but even subtle variations in temperature can be critical to animal survival. (Heschong, 1979:1)*

While this example may be displaced from human thermal sensation, it supports the thermal capacity of architecture to achieve a deep impact on human-perceived environments by organising matter and energy through only minor temperature gradients.

3.5 Synthesis, Conclusions and Propositions

Theoreticians such as Böhme, Hill and Moholy-Nagy place focus on the immaterial aspect of architecture, which have the capacity to form architectural articulation. Nevertheless, while placing emphasis on the environmental and immaterial aspect of architecture, they subsequently accentuate the notion that these two domains, material and immaterial, remain somewhat separated, rather than domains that are to be understood as a whole. In the physics-based description of environment and its boundaries and relations, Oke and Addington suggest a more open-system approach to the understanding of an environment's behaviour and properties through the notion of transition processes. A boundary is not a fixed, solid entity, but a fluctuating condition that is continuously being constructed. The additional notion of a moving boundary demarcating an inner and outer environment, as drawn from systems theory by Simon, extends the intricacy of environmental construction based on human, architectural and climatic factors. These perspectives stand in opposition to common boundary definitions in architecture, as formulated by Evans, and promoted by current isolating principles, as discussed here and by Kiel Moe.

Within this chapter, a series of architectural examples, engineering assessment methods, and philosophical, anthropological, neurological, physics and architectural theoretical notions have been presented. In individual cases, and as a collective examination, it is asserted that it has been shown how architecture can be understood as the organisation of matter towards a human-oriented environmentally sustainable architecture. And, in many cases it has been laid out how such processes can be imagined and made operational in bounded organisations enabled by the control of exergetic capacities.

By following the notions of open systems, in contrast to isolated systems, Environmental Tectonics positions itself closer to the approaches of Free-Running Buildings and Performance-Oriented Architecture. Of immediate difference, however, is the intent here to construct environmental sensations by architectural intervention. In FRB and POA, current research and its applications seem to be oriented towards fulfilling comfort temperatures and reaching energy codes as its primary provisions. In relation to FRB, Nicol and Humphrey illustrate a simplified model for thermal assessment. It is an interesting approach, particularly as they illustrate the human thermal adaptive capacity and mechanisms, but at the same time it reduces the potential for architecture to advance human life, relating comfort to external temperatures only.

Additionally, if considering Uexküll's concept of Umwelt in the subjective sense of the world, it is difficult to continue on a path of general descriptions of human comfort and human sensations. What appears necessary is an approach that allows the specificity of the environment, as of the human, to become part of the architectural design methodology.

Based on the examination and arguments provided within this chapter, a first set of propositions for an human-oriented environmentally sustainable architecture can be formulated. These are directly related to the initial hypothesis and research questions posed in the preliminary section to this chapter.

Proposition 1
Environmental Tectonics is a matter-based architectural practice.

The proposition suggests the idea of architecture as constructed by gaseous, fluid and solid phases of matter and by the ability to change from one state to another in the manifestation of architecture. It recognises that architecture is a shared authorship, influenced and organised as a non-discrete system, not confined by current architectural practice on boundary making.

Proposition 2
Environmental Tectonics is aesthetics expressed by the organisation of matter.

When the aesthetic dimension is based on how we perceive the world, the proposition suggests the idea that the organisation of matter is directly connected to the aesthetic articulation in architecture. Hence, it repositions the predominant notion of aesthetics from that of a visually described phenomenon to a multi-sensorial prescription made instrumental by the organisation of matter.

The two propositions suggest, firstly, an instrumental agenda, the organisation of matter in bounded and unbounded modes. Secondly, instead of pointing directly to energy efficiency as an aim, they point to the construction of environments and the derived aesthetics, which subsequently have the capacity to improve the current energy imbalances in the built fabric. This statement is based on the findings in FRB to lower the use of fossil-based energy by decreasing the difference between thermal comfort and external temperatures based on human adaptation, thereby decreasing the need to cool or warm spaces mechanically.

4

Tectonics

4.0 Preliminary

The Introduction chapter outlined how principles of architectural construction and its potential capacity as design instrumentation may enable a new environmentally sustainable architecture. In relation to environmentally oriented architectural design construction methods and models, it was asked:

What is the basis for an architecturally elaborated construction model and how can it be formulated and made instrumental for environmental architectures? (Q2)

To approach this question, it is necessary to elaborate upon the relevance of why and how tectonic constructions in architecture is essential as an aspect of a future architectural discourse and field of inquiry. This initial theoretical orientation is based on tectonics' both applied and philosophical construction aspects, and its believed instrumentality for a future environmentally sustainable architecture. Of importance is that it may enable architectural making to be the primary means and mode to construct sustainable environments over technical post-built applied mechanisms. Tectonics is considered a highly developed form of architecture (Hartoonian 1994) that expresses the structural forces and the adequate expression of material assemblies by joints to reach what architectural theoretician Kenneth Frampton has described as *'the poetics of construction'* (Frampton 1995). As argued earlier, the Digital Tectonics branch has inherited the structural aspect as a driver for tectonics-oriented work. In this chapter, tectonics is examined more thoroughly to identify its discourse and investigate its potential for application towards an environmental architectural agenda. In this manner, the chapter follows the discussion and propositions of the prior chapter towards an approach that points simultaneously to a physical functionality of construction and the philosophical aspects of building. Currently, tectonics in architecture is principally perceived and described post-construct, identified in built work by theoreticians through analysis. This can be seen in the work of the aforementioned and authoritative writings of Kenneth Frampton, Marco Frascari on his analyses of the detail in Carlo Scarpa's work, and Carles Vallhonrat's analyses of Louis Kahn's work, among others. Hence, it is descriptive in character, rather than methodologically prescriptive, as was explicitly designated in the question above.

In moving towards an architectural agenda, the foundation of which is related to tectonics but with an aim of adding environmental sustainability, it becomes necessary to understand and elaborate upon an instrumental methodology that allows a tectonic approach to re-orientate itself towards aspects of environmental properties. In addition to the question above, it is crucial that we ask:

How can tectonics be oriented towards and become instrumental for an approach to environmentally sustainable architecture? (Q6)

What modes of architectural instrumentation are applicable to support this orientation? (Q7)

In order to approach these questions, the chapter will firstly locate the etymological and theoretical foundation of tectonics in architecture. The reason for this is to search for the meaning of how the construction end effect receives the term and notion of 'tectonic'. To approach and exemplify the question, an examination of the work of one architect in particular is conducted, following the case study methodology described in the Methodology chapter (chapter 2). This gives an inroad to the subsequent sections of Addition and Transformation, which investigate in greater detail and position specific operations with the aim of supporting a more detailed methodological design approach in response to the questions above. These sections are then followed by an attempt to position the foremost endeavour for an Environmental Tectonic approach in the section on Membrane. This section specifically points back to the theoretical discussion of the previous chapter, Environments, and forward in terms of positioning the architectural probes in Probes (part 3) of this thesis. Following the theoretical foundation, which takes place through exemplification and advocated operations, lastly, a set of propositions is suggested to move tectonics into a prescriptive and contextual instrumentality in architecture towards the extension, Environmental Tectonics. The chapter also serves as a basis to approach a computational methodology adhering to the conclusions of both this and the previous chapter in the following chapter, entitled Computation.

4.1 Notes on Tectonics

As initiated in the previous chapter, Environments, an instigating look at the etymological foundation of tectonics is implemented. From the Oxford English Dictionary (OED), tectonics is firstly situated in the field of geology, referring to tectonics as *'relating to the structure of the earth's crust and the large-scale processes which take place in it'*. Secondly, one is informed about the origin of the meaning of the word, originally from Greek, *tekton*, from *tektonikos*, meaning *'building or construction'*. As with environments, tectonics has different meanings in different academic fields and, as will be discussed, tectonics carries different meanings within the field of architecture itself. This section aims to ground the meaning in the current state of the word for this to be positioned and specified, allowing further correlation and causality with other aspects of this work from both a theoretical and an applied research perspective.

Historically, the entry of tectonics into architecture is often related to Karl Bötticher's publications from 1843-1852 on *Die Tektonik der Hellenen* (Vallhonrat 1988; Liu & Lim 2006); however, Kenneth Frampton points back to Karl Otfried Müller's *Handbuch der Archäologie der Kunst*, published in 1830 as the earliest positioning of tectonics. Frampton refers to Müller:

> *Wherein he defines tektonische as applying to a series of art forms such as utensils, vases, dwellings and meeting places of men, which surely form and develop on the one hand due to their application and on the other due to their conformity to sentiments and notions of art. We call this string of mixed*

> *activities tectonic; their peak is architecture, which mostly through necessity rises high and can be [a] powerful representation of the deepest feelings. (Frampton, 1995:4)*

The text speaks of a broad group of design activities resulting in different artefacts, with architecture as the summit. Here, it is interesting to note the relationship to the Greek etymology of tekton, meaning construction, which is not necessarily bound by the objective of architectural construction. Müller points to architecture, but does not exclude the production of other artefacts by the *'mixed string of activities'*.

In Bötticher's *Die Tektonik der Hellenen*, the analysis of the work results in the description of *Kernform* (core-form) and *Kunstform* (art-form), which gives different meaning to different parts of an architectural construct. Here, the distinction of the core-form of the building and the applied art-forms are defined by their functions and their symbolic meanings in Hellenic art (Hartoonian 1994). The segmentation of architecture into two forms by Bötticher was further elaborated by German architect and theorist Gottfried Semper, however, developed into an argument of the intrinsic relations between the two architectural aspects.

From this, an argument of the word tectonic was developed and presented by Semper in his *Die Vier Elemente der Baukunst* (1851). Here, he moves beyond the theoretical position of Bötticher's twofold notion of tectonics and the priest and architectural theoretician Marc-Antoine Laugier's primitive hut from 1755 as a predominant model of the origin of architecture. By decomposing the architecture of the Caribbean Hut [Fig. 4.1] that he observed during the London World Expo in 1851 into four fundamental elements: (1) earthwork, (2) hearth, (3) framework/roof and (4) enclosing membrane (Semper, 2004 [1860]). The segmentation is further grouped into two categories, with the earthwork and hearth belonging to the topography and mass, categorised as the 'stereotomic', while the spatial and lightweight framework/roof and enclosing membrane are categorised as the 'tectonic'.

To Semper, and later Frampton, the articulation and meeting between these two, stereotomic and tectonic, forms the quality of architecture (Frampton, 1995:86), with Frampton elaborating that the quality of architecture lies in the *'interplay of the three converging vectors, the topos, the typos, and the tectonic'* (Frampton, 1995:2). The meeting becomes a focal point in the Semperian description of tectonics, with an extensive focus on material assembly, how materials and elements are joined together, as a way to express the properties of the material in relation to their application in architecture. In his seminal work *Der Stil in den Technischen und Tektonischen Künsten oder Praktische Ästhetik* from 1860, now translated to *Style in the Technical and Tectonic Arts; or, Practical Asthetics* (Semper 2004), numerous examples and descriptions elaborate upon the emphasis on the material properties and the joining of materials into assemblies. In his four categories listed above, this has particular emphasis throughout his work on the enclosing membrane (Frampton 1995), with a particular interest in the textile as a derivative of the knot and the seam. Both seam and knot emphasise Semper's notion of tectonics in architecture.

The joint as a fundamental aspect revealing the quality of architecture is further emphasised in the writings of architectural theoretician Marco Frascari. Through the

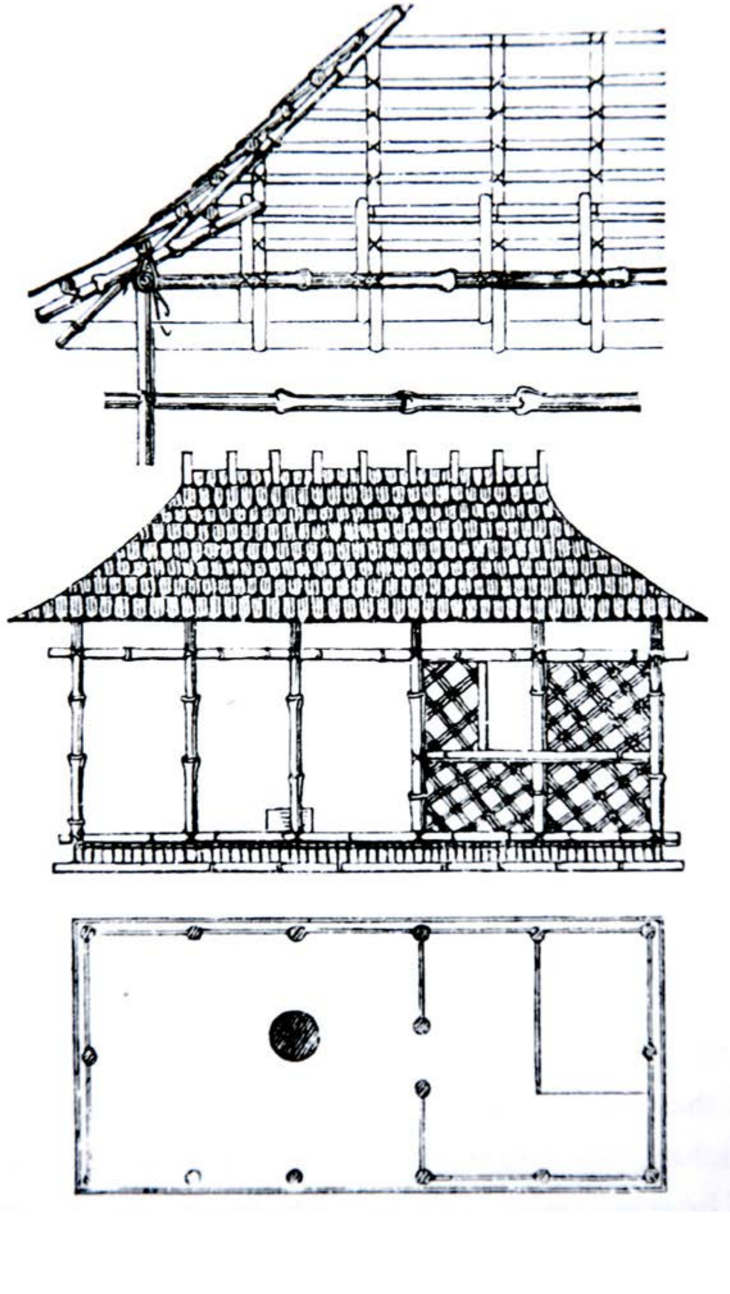


Figure 4.1

Carribbian Hut (1851) illustrating the tectonic of the building by its assembly, joints, structural clarity, and definition of textile walls. Drawing by Gottfried Semper.

work of the Italian architect Carlo Scarpa [Fig. 4.2], Frascari exemplifies how the joint per detailing has meaning beyond its local application of connecting two or more elements together (Frascari 1984). Frascari posited that the articulation of the detail, which essentially is scaleless, is the central aspect of tectonic articulation. While Frampton asserts the importance of structural integration in the joint, so as to achieve 'structural ornament' and not 'ornamented structure' (Frampton, 1983, 1995, 2011), this appears of less concern to Frascari. The importance of structural articulation of force is also emphasised by Carles Vallhonrat, with an almost authoritarian emphasis on the importance of expressing gravity, as he stated:

> *Tectonics depends upon a very few fundamental aspects of the physical world. One, of course, is gravity and the physics that goes with it. Gravity affects what we build and the ground beneath it. Another aspect is the structure of the materials we have, or make, and a third is the way we put those materials together. (Vallhonrat, 1988:123).*

Frampton elaborated:

> *Despite the critical importance of topography and light, the primary principle of architectural autonomy resides in the tectonic rather than the scenographic: that is to say, this autonomy is embodied in the revealed ligaments of the construction and in the way in which the syntactical form of the structure explicitly resists the action of gravity. (Frampton, 1983:27)*

And:

> *The tectonic remains to us today as a potential means for distilling play between material craftwork and gravity, so as to yield a component which is in fact a condensation of the entire structure. We may speak here of the presentation of a structural poetic rather than the re-presentation of a facade. (ibid:28)*

This formulation appears to be connected to the writing of Eduard Sekler, in his essay *Structure, Construction, Tectonics*.

> *When a structural concept has found its implementation through construction the visual result will affect it through certain expressive qualities which clearly have something to do with the play of forces and corresponding arrangement of parts in the building yet cannot be described in terms of construction and structure alone. For these qualities, which are expressive of a relation of form to force, the term tectonic should be reserved. (Sekler, 1965:89)*

In addition, Vallhonrat, in his analysis of architectures, with particular interest in the work of Louis Kahn (Vallhonrat used to work in Kahn's office), appears largely oriented towards gravity. While Frampton positions gravitational force for tectonic articulation in the foreground, he renders it nevertheless more nuanced while assessing work for the definition of tectonics, as he posits:

Figure 4.2

The elaborate joining of materials at Tomba Brion Cemetery (1978) by Carlo Scarpa. Photo by James Butler.

> *One has in mind a whole range of complementary sensory perceptions which are registered by the labile body; the intensity of light, darkness, heat and cold; the feeling of humidity; the aroma of material; the almost palpable presence of masonry as the body senses its own confinement; the momentum of an induced gait and the relative inertia of the body as it traverses the floor; the echoing resonance of our own footfall. (ibid:28)*

This also aligns more closely to his description of architectural quality based on the trio of the tectonic, the topos and the typos as stated above. In addition, in Semper's taxonomy, earthwork and hearth belong to the stereotomic, which is a direct continuation of contextual topography, which is therefore related to the local specificity of the material's availability and the surrounding terrain. However, the notion of tectonics remains oriented towards the structural and gravitational force field. Within this argument, as in this thesis, a philosophical perspective formulated by the German philosopher Martin Heidegger is a central source of the move towards an extended formulation.

Heidegger revisits the Greek terminology and the etymology of the early thinkers with particular reference to Plato and Aristotle's thoughts on the process of making (Heidegger, 1977 [1954]). The objective is to understand technology in relation to society and culture in order for humankind not to be suppressed and chained by technological processes. Heidegger explains that technology is not equal to technological, in that technology relates to instrumentality and causality. From the Aristotelian philosophy onwards, four causes exist; causa materialis (the material, the matter out of which something is made), causa formalis (the formation, the shape into which the material enters), causa finalis (the end, to which something is related to its requirements) and causa efficiens (the effect brought about by the finished something). According to Heidegger, we have only been interested in the result, the effect of things, causa efficiens. This results in a reduction to one of the four unified causalities that makes something appear. In contrast, with reference to Plato, Heidegger explains that when the four causes are unified, *'every occasion for whatever passes over and goes forward into presencing from that which is not presencing is poieses, is bringing-forth [Her-vor-bringen]'*. Heidegger elaborated:

> *It is of utmost importance that we think bringing-forth in its full scope and at the same time in the sense in which the Greeks thought it. Not only handcraft manufacture, not only artistic and poetical bringing into appearance and concrete imagery, is a bringing-forth, poiesis. (ibid:5).*

The bringing forth and making something appear is based on the unison of the four causalities above, suggesting a broader scope of causes than the current custom of simply making towards an end. What this entails is, for Heidegger, a deeper process of technology that is not bound to the idea of technological artefacts, but to the creation of something more profound. He elevates the agenda of a technology practice into a realm of revealing what is concealed to us and introduces us to the Greek *Aletheia*, meaning revealing, which is a bringing forth by the practice of the four causalities.

From this, the word technology is linked to the act of revealing, as technology is derived from the Greek technikon, from which *techné* is also derived. From the dictionary of philosophy (DOP, 1942):

> *(Techné) The set of principles, or rational method, involved in the production of an object or the accomplishment of an end; the knowledge of such principles or method; art. Techné resembles episteme in implying knowledge of principles, but differs in that its aim is making or doing, not disinterested understanding. (DOP, 1942)*

The notion of techné thus belongs to making in terms of the activities and skills of craftsman and in the minds of the fine arts, by bringing forth, resulting in poiesis. The extension stressed by Heidegger is the aspect of techné that is linked to episteme, referring to a twofold of knowledge (making and knowing) in a process of making something appear, with the clear emphasis of revealing over the mere process of making an artefact.

From Heidegger, pointing to Greek philosophy, Frampton elaborates upon the aforementioned formulation of tectonics as *'the poetics of construction'* (Frampton 1995). The formulation brings together the symbolic meanings applied in Semper's four elements and the poiesis asserted by Heidegger in the process of revealing. This in turn points to the activity of construction and not solely to the observed articulation of structure. This form of transcendence beyond mere load-bearing functionality into an orientation of a tectonic architecture has been eloquently expressed by Frascari in his double-sided phrase, *'techné of logos'* and *'logos of techné'*, translated as 'construction of meaning' and 'meaning of construction' (Frascari 1996; Beim 2004; Frascari 1984). While Frascari's phrase speaks elegantly about the twofold and extended aspects of construing and construction, and of meaning, it is unclear whether it relates to the full unison of causes or predominantly to the effects of the artefact, causa efficiens.

Furthermore, it is important to recognise that techné is bound by an external agency for the act of revealing. In the four causes mentioned above, an agent is needed to unfold and unify the causes to illustrate the essence of things.

It is also important to recognise that techné is not bound to revealing gravity, even though Heidegger refers to construction, but to a general objective of revealing something. Thus, if tectonics resides in techné, it cannot be upheld by gravity, but must be open to diverse causes and objectives. Also, if tectonics could be bound by the expression of gravitational forces, tectonics would only be perceivable by the eye, and this is, in itself, in opposition to the notion of revealing in its broadest sense. Referring back to the previous chapter and advancing the argument here, Heidegger posited:

> *We, late born, are no longer in a position to appreciate the significance of Plato's daring to use the word eidos for that which in everything and in each particular thing endures as present. For eidos, in the common speech, meant the outward aspect [Ansicht] that a visible thing offers to the physical eye.*

Plato exacts of this word, however, something utterly extraordinary: that it name what precisely is not and never will be perceivable with physical eyes. But even this is by no means the full extent of what is extraordinary here. For idea names not only the non-sensuous aspect of what is physically visible. Aspect (idea) names and is, also, that which constitutes the essence in the audible, the tasteable, the tactile, in everything that is in any way accessible. (Heidegger, 1977:9)

In the book *Semper and the Problem of Historicism*, Norwegian architectural scholar Mari Hvattum pointed to this understanding of the larger meaning inherent in techné as imbedded in Semper's thinking on making. Hvattum stated that the act of making is not an effort that is bound by the materialisation of architecture alone.

I believe Semper's notion of making has more in common with what Aristotle would call poises: a particular mode of making informed by a particular kind of knowledge. This poetic knowledge was precisely what Aristotle required of the poet: the capacity to recognise and represent the concealed unity of human action. Architecture, in Semper's view, involves precisely such a 'thoughtful making': a making informed by the knowledge of human praxis, whose role is to clarify and embody such praxis. (Hvattum, 2004:81)

In the discussion between architectural theorists of the time on the autonomy of architecture as a field, imitation and referentiality were argued to be of importance. In the case of nature, imitation, however, according to Semper, was to exceed a mere expression and move beyond it to a deeper understanding and integration of imitative processes while converting it into the architecture. Hvattum elaborated on Semper's statements.

The origins of architecture, he insisted, must be sought not in architectural form itself but in the preconditions which shaped it: 'the constituent parts of form that are not form itself, but the idea, the force, the task, and the means'. (Hvattum, 2004:65)

A relationship to Heidegger's manifold description of techné becomes evident in Semper's thinking, as the form, causa formalis, is not to be understood as the singular making, or imitation. Rather, the underlying causes from which it has developed uphold the most significant value. This form of argument and architectural orientation is perhaps most strongly elaborated upon in his *Stoffwechseltheorie*, in which Semper outlines the importance of understanding and elucidating the transformative processes in order to perceive the meaning of an object.

A particular method of artistic representation is inherent in each material because each has properties that distinguish it from other materials, and each demands its own treatment or technique. When an artistic motive undergoes any kind of material treatment, its original type will be modified; it will receive,

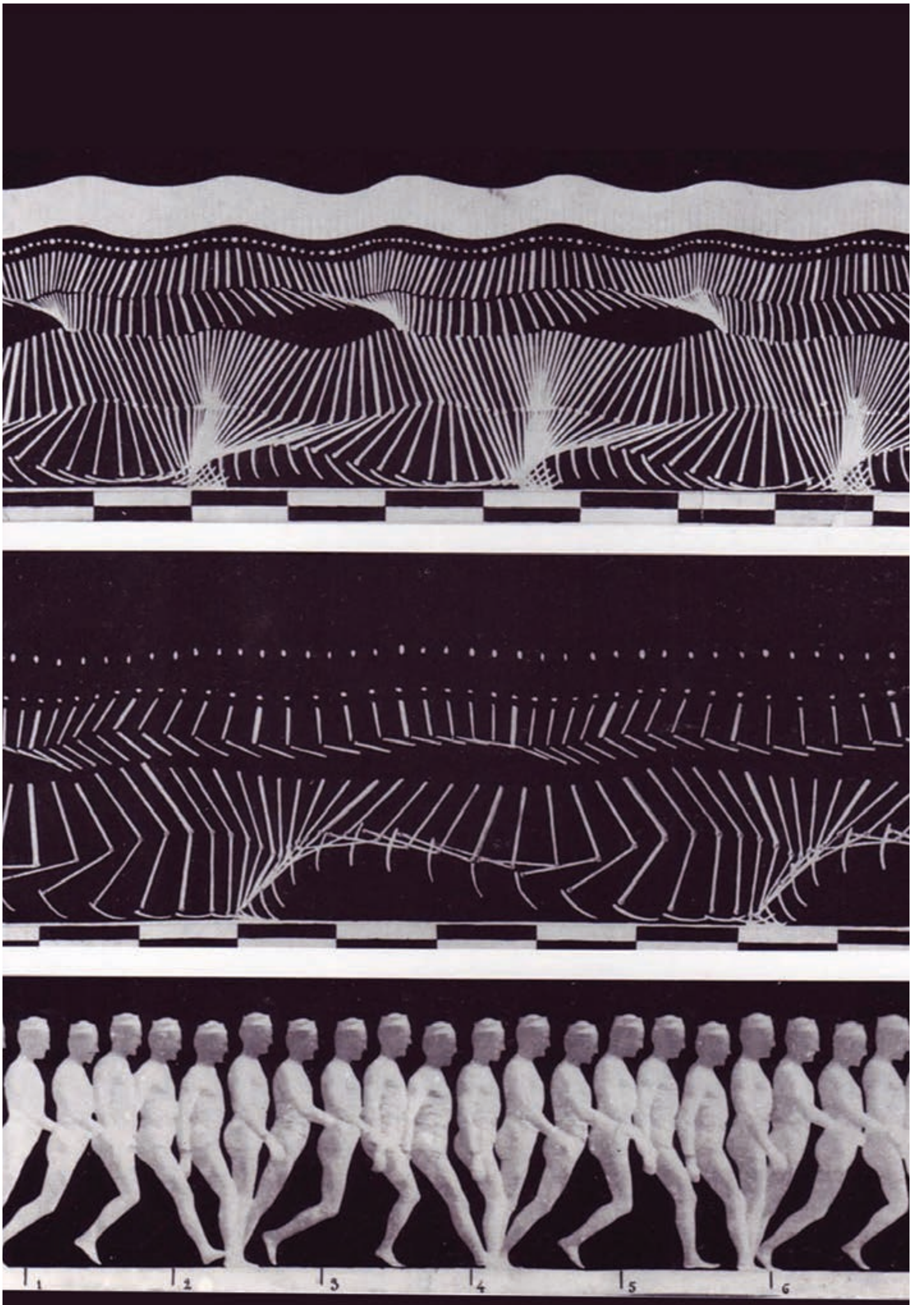


Figure 4.3

Human locomotion traced to understand the movement of body parts and their relations. Photo by Etienne Jules Marey.

> *so to speak, a specific coloring. The type is no longer in its primary stage of development, but has undergone a more or less pronounced metamorphosis. If the motive undergoes a new change of material [Stoffwechsel] as a result of this secondary or even multiple transformations, the resulting new form will be a composite, one that expresses the primeval type and all the stages preceding the latest form. If development has proceeded correctly, the order of the intermediate links that join the primitively expressed artistic idea with the various derivations will be discernible.*
> *(Semper, 2004:250)*

It is important to remember that 'motive' in German has a broad definition, as it can refer to the artistic image as well as the underlying idea, echoing his previous statement above. The concept of Stoffwechsel as suggested by Semper thus links directly to the Greek notion of making and offers a central pathway to processes of revealing or making something appear towards a deeper understanding and acting in the world through architecture. The notion of Stoffwechsel can therefore be proposed as an example of unison of the four causalities of techné. Furthermore, inherent therein is the argument of a transformative process, which progresses in forward-moving steps, where we can trace the development backward, and therefore also the dynamic advance of the intention and meaning induced by the making agent.

An example of this proposition can be obtained outside architecture. Tracing progression in order to make a form discernible in a transformative process is not dissimilar to the process of understanding complex transformative geometric positions by animals. Such processes were investigated by Etienne Jules Marey, enabled by the development of a new camera that would capture through high-speed shutters the locomotion of birds, horses and humans as examples. Such an analogy of capturing, understanding and advancing architecture has previously been suggested by theorists of the actor-network-theory (ANT) in order to move towards a more profound integration and development of aspects that have an influence on architecture (Latour & Yaneva 2008). The ability to make something discernible through transformative processes applies to both a design space (pre-built condition) and a constructed space (post-built condition).

With a theoretically extended meaning of tectonics, through the taxonomy and integration of the four causes and its relation to Semperian transformative processes, the next section attempts to apply these notions to potential applied methods of making. In so doing, the next sections investigate and exemplify the design and constructed spaces, and how transformative processes can reveal to the observer the various derivations by gradual modifications. Specifically, the first section intends to illustrate transformative processes in a design space by additive processes in architecture, with the following section aiming to illustrate matter-based architectural transformation processes in a constructed condition.

Figure 4.4

Assembly by Utzon of simple elements to construct a complex 3-dimensional undulating surface geometry in yellow, with its white sibling created from all-different planar curved geometries to construct a similar complex surface. Photo by Isak Worre Foged.

4.2 Addition

Case studies are conducted in an attempt to illustrate and integrate the above notions of techné and Stoffwechsel for later foundational propositions. These are selected from the perspective of identifying tectonic instrumental principles and processes of architectural making identified within the above notions towards appearance.

The work of Danish architect Jørn Utzon is examined as cases of such processes. Utzon extensively created, not only highly acknowledged tectonic buildings (Frampton 1983; Frampton 1995; Frampton 2011), but also more importantly, implicit processes and methods from which his work appeared. An additional reason for studying Utzon's work is his fascination and indirect orientation towards biological processes (Prip-Buus 2009; Weston 2008). Such integration to elevate architecture was as also discussed by Semper, Schlegel, Goethe, Alberti et al (Hvattum 2004; Semper 2004; Steadman 2008) when positioning architecture as a field of study and practice. Much can be observed from the three cases chosen, but the work here focuses on the way in which an idea or form appears through the process of additive principles. Each case is observed through the four causalities of Heidegger, inserting a classification system of tectonics through which the work can be understood from a perspective of making and revealing.

Bricks

The industrial 'bricks' [Fig. 4.4] developed by Utzon are perhaps the smallest and simplest elements he designed. Yet their development was initiated as a method to create the complex structure used for perhaps the largest structure he created, the Sydney Opera House shells. When using conventional industrial elements based on rectilinear geometries, such as a standard brick, gaps would appear between the elements when angling them to follow the curve of the shells. This created a non-continuous surface and a contact between the elements reduced to a minimum on the concave side of the assembled elements. A convex/concave forming applied the necessary modification, in what can be described as the ends of the elements. This created a bead and cove cross section similar to what occurs in strip-planking a boat hull. This allows the elements to increase surface contact, rotate in their plane as hinges, and close the gaps during the angling of the elements in relation to their 'neighbours'. Utzon stated:

> *This ensures building economy and the expressiveness automatically arising as the result of mass production and the many repeats of the small number of elements in different variations. (Utzon, 2002 in (Prip-Buus, 2009:27))*

In this, identification of the four causalities – causa materialis, causa formalis, causa finalis and causa efficiens – is possible. Within the brickwork we have knowledge of the material, the initially elaborated form of the element and the resultant final form appearing by the agency of the maker. From this its structural and expressive effects

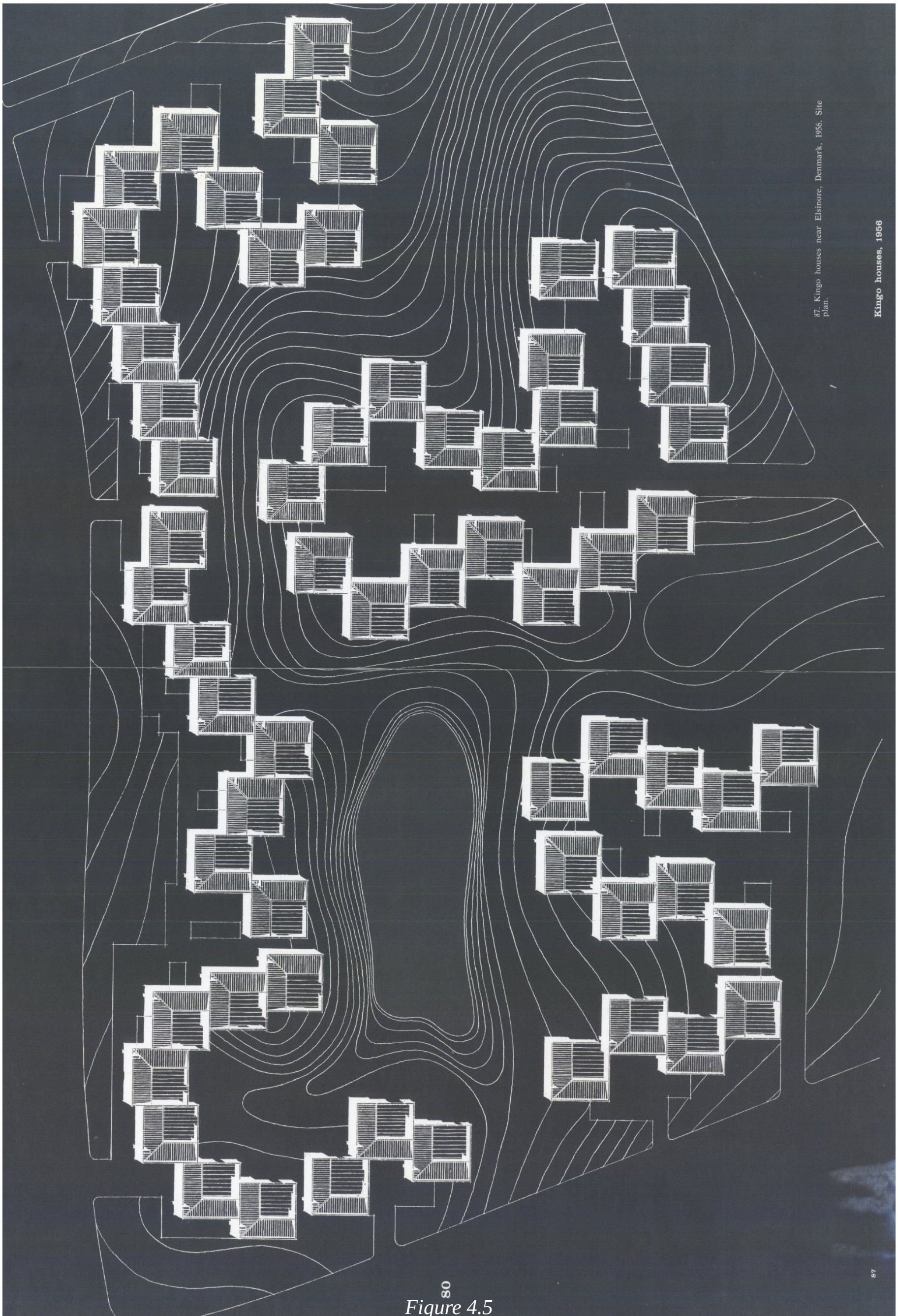


Figure 4.5

Kingo Houses plan layout organised in strings of elements on the site. Elements are organised according to each other and the undulating topography. Drawing by Jørn Utzon. Obtained from the Utzon Archive, Aalborg University.

arrive. It can, however, be suggested that the material integration and exploitation of the material properties is less developed than the three other aspects. It is less clear to what extent the material used is chosen based on inherent characteristics. While this approach proved infeasible in the construction of the opera shells, it underpinned an approach to making that predated Peter Pearce's later notion of how *'structures in nature is a strategy for design'* by stating:

> *Systems can be envisaged which consist of some minimum inventory of component types which can be alternatively combined to yield a great diversity of efficient structural forms. We call these minimum inventory/maximum diversity systems. (Pearce, 1990:xii).*

Pearce undertook a series of experiments, which were predominantly orientated towards Platonic and Archimedean solids mimicking forms observed in nature. Pearce illustrated through these exercises the ability of the simple to reach articulated complexity through the principle of addition. From the more complex assembly methods by Pearce, it can be argued that the simpler element proposed by Utzon has the inherent capacity of greater modes of assembly by its simple interlocking, suggesting a joint between parts, through its convex/concave geometry. The understanding of complexity created from assemblies of smaller simple parts appears to have initiated the reverse process of designing smaller simple parts that could succinctly be used as a method for a design process, which would be open to a reading of multiple aspects simultaneously.

Kingo Houses

In Elsinore, in north Sealand, Denmark, Utzon appears to continue this instrumental method on a very different scale. Here, on an undulating ground surface with a small lake, houses become elements, which by their simple boundary geometry allows a free organisation of dwelling elements [Fig. 4.5]. Utzon posited:

> *Building is in a principle a process of putting things together, i.e. of adding. The individual courtyard houses, which are an accretion of bricks, are not additive architecture, though the development of the whole deserves the name. (Utzon 2009)*

In this case, the bricks creating the houses are no longer perceived as additive elements. This indicates a shift, not only in scale, but also in which parts of a building are addressed as belonging to the additive principle. In the above case of bricks, elements were able to construct a complex surface, in the case of dwellings; they are able to construct a building network informed by local specificities. The plan reveals, beyond the topography, the courtyards, and suggests openings related to the individual houses, which were intended to have a specific view of the outside while reducing the views into internal spaces. By using the simple geometrical form, the square, elements

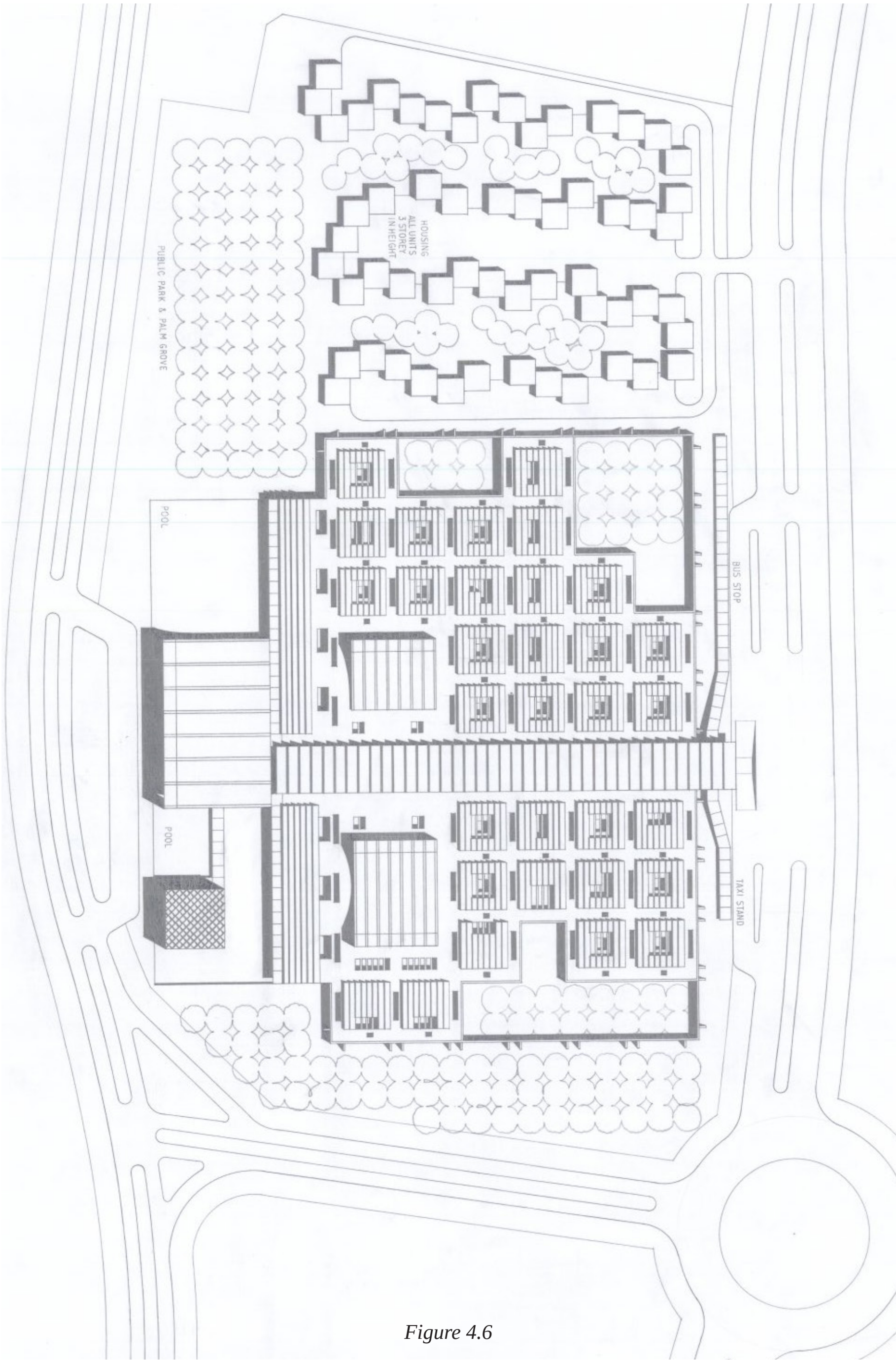


Figure 4.6

Kuwait National Assembly (1982) illustrating the different elements and their organisation inside the boundary wall. Drawing by Jørn Utzon Drawing obtained from the Utzon Archieve, Aalborg University.

(individual houses) could be organised not only freely against each other, but also freely rotated, allowing a high design manoeuvrability in the making of the contextual layout of the elements, addressing multiple design issues simultaneously and in this process making the context itself understandable by iterations of organising the elements in various formations.

As a functional reference to biological systems, applied in the context of the aforementioned theoreticians' reference to the same, the segregation of elements in a system, as can be read by the plan layout, allows a greater capacity to adapt locally for the improvement of the entire system. The reason for this is that development can occur without conflicting interests between parts. In the description of animal diversity and the development process, Sterelny stated:

> *Perhaps it is no accident that segmented-bodied arthropods are far and away the most diverse lineage of animals. For once segmentation has been invented, natural selection can specialize segments to new roles. Thus their limbs have often been converted into feelers and various other specialized biological machines. (Sterelny, 2007:64)*

In the Kingo Houses, it can be observed how strings of elements are organised for the benefit of the individual elements and the groups they belong to, and for the profit of the overall organisation in relation to the contextual condition. Obviously, the biological analogy is representational, but it nevertheless exemplifies the properties of such formations in relation to an inner environment of infrastructural organisation and an outer environment of contextual adaptation.

While Utzon studied biological forms and processes (Weston 2008; Utzon 2009), he most likely did not have this biological principle in mind. Nevertheless, it is evident from a series of other projects following the Kingo Houses – for instance, Farum Center from 1966, Jeddah Stadium from 1967 and College Campus in Herning from 1969 – that this form of design methodology enabled the capacity to gradually develop a design into a set of parameters, while maintaining and developing the initial idea at the same time by the use of simple, well-created elements.

Returning to the four causes, the project is using bricks with a specific materiality; however, this seems, again, of less importance in relation to the organisation and progress of the overall system and formation. While form development, final form and its effects are readable, the aspect of material is less integrated, hence decreasing the holistic unison of causes in techné.

Kuwait National Assembly

In the case of the projects mentioned above, elements can cluster, organise and expand freely, limited only by the boundaries of the site. In the case of the Kuwait National Assembly [Fig. 4.6], which was designed in 1972 and completed construction in 1982, Utzon constructed a strict boundary in the plan outlining the space in which elements can be organised. The construction of the strict boundary is done, according to Richard Weston (Weston 2008), as an approach to inserting a contextual framing that is not present on site.

In comparison to the more free organisation of the Kingo Houses and the unbounded conditions of the brick system, the Kuwait National Assembly is much more restricted in its organisational potential due to the stringent boundary framing. Additionally, while the living units in the Kingo Houses where identical, Utzon operated with four elements in the Kuwait National Assembly: the assembly halls, the reception rooms and halls, a covered square and a series of functional modules including the remaining facilities. While all are based on the same grid formats, able to align in a plan lattice, the sizes of the elements are related to the quantity: many smaller modules and few larger ones. Also, it is worth indicating that the smaller and many functional modules are created with a generic stringent outer boundary, similar to the overall framing of the complex. This allowed the free organisation in the grid, while each module could be differentiated on the inner boundary courtyards existing in every module. This in itself allows variation while maintaining the instrumentality of the system described in the cases above.

The reverse capacities of the segmented bodies can be suggested to be the case for the National Assembly, by the biological analogy of organs in a body that are fighting for space and are thus only able to accommodate modifications if other elements modify in sync. The relationship between the elements is there, however, in stringent relationships and hierarchies, as any change has direct consequences for the organisation of the whole. Architect and architectural theoretician Christopher Alexander proposed the biological analogy in relation to harmony-seeking organisations:

> *As cell division progresses, new cells take shape within the context of the surrounding cells, and, at the same time, adapt, so that they are shaped by these surroundings, and simultaneously play an active role in shaping their surroundings. (Alexander, 2009:11)*

This statement links directly to Simon's descriptions of inner and outer environments in complex systems. Any module of the Kuwait Assembly is based on its own internal logic, its specific courtyard design and its relation to its neighbours along the module's boundaries. With the framing wall, reception spaces, assembly halls and covered square positioned, the large series of modules could be freely organised. The modules were organised in relation to connectivity to building entrances, general building infrastructure and connection to neighbouring modules, and rotated as needed to accommodate the orientation and layout of the diverse courtyard spaces defining the inner spaces of each module. As one module is rotated or moved, another must take its place and the neighbouring modules must be re-considered for their relation to the new module. Development of the design solution and freedom during iterations of the whole scheme are maintained, making it clear how and why modifications of the organisation are developed.

As with the previous cases, and in its specific similarity to the Kingo Houses, when evaluated against the four causalities, the National Assembly in its organisational scheme appears less oriented to the materiality of the building than to the evolution of the form development, final form and effect.

Element, System, Formation

In the three cases above, three levels of instrumentality were identified.

Firstly, the level of the individual element is described with which the fundamental conditions of geometry are defined. In the first case, the elements of the bricks are proposed for their material structural characteristics in compression, ease of production, ease of addition and ease of building by hand. Forms are orientated towards a low-cost industrial construction process, with a high-tactile-quality material, ensuring maximum freedom in their arrangement when elements are added to each other. In the second and third cases, the element is proposed based on its ease of spatial connectivity and expandability in relation to changing organisational spatial requirements. In the latter group, the scale allows for two levels of articulation of each element, an outer generic form serving as the surface of connectivity and an inner, potentially more diverse and unique form, as can be seen in the Kuwait National Assembly.

A second level can be observed by the way the elements connect and interact as a system. Again, in the case of bricks, even with simple elements, modes of connectivity and force interchange are necessary to express and understand. Placing the bricks in such a way that their edges meet is complicated and infeasible in terms of force transition between elements. The fact that the bricks designed by Utzon have convex/concave surfaces speaks of their joining in a particular way, while they are flat on two other surfaces, suggesting stacking. At the system level, elements must either provide the means for interlocking or insert a connective tissue keeping the elements in their intended positions, such as mortar. The systems in the second and third cases are similar to the bricks, able to extend the structural functionality of the elements by assembly, as walls or entire element modules can be supporting or directly shared, as is the case in the Kingo Houses. Here, the integration between element and system starts to form a unity, which, however, may cause reduced agility in the overall composition if the connection is strictly maintained during design progression. This in turn changes the element from its initial simple geometry to a more complex composite element by the fixed connection to other elements.

When an element and a system are articulated, a third level of formation can be observed. While Utzon initially intended the opera shells to be produced by many small elements, the full formation of the system and elements are only to be read in the model placed in the Utzon Center. When elements and a system are articulated, formations can be sought and elevated to respond not only to themselves (inner environment) but also to their context in a highly adaptable way (outer environment). This can be seen in how this design method was applied in numerous projects, in various cultural, programmatic, geographical and topographical conditions from Jeddah to Elsinore.

The ability of high design manoeuvrability and contextual adaptation by the instrumentality of the three interlinked levels suggests a way in which the causes imbedded in techné can be made operational and arguably aligns with the modus operandi similar to the Semperian Stoffwechseltheorie. If the aforementioned notions are observed in a form of reverse perspective, architect and architectural theoretician Carles Vallhonrat exemplifies the potential consequences.

First Traversina Bridge (1996) by Jürg Conzett. The bridge is made of elements that gradually modify in relation to the changing structural functioning across the span. Photo by Conzett Bronzini Gartmann AG.

> *The one technical innovation that has affected our art is the increase in the size of the increments with which we build: the size of glass, or the size of rolled steel, for instance. This development has brought about a change in our sense of scale, for the sizes have changed in relation to our customary cultural sense of good measure. This increase in the size of construction elements has also tended to make more remote and unclear the sense of the articulation of parts that one used to use to facilitate a reading of the behavior of materials. (Vallhonrat, 1988:131)*

Besides the work of Jørn Utzon, architecture that intentionally or unintentionally appears from these processes of hierarchical and instrumental order between elements, system and formation can be observed in the work of Swiss engineer Jürg Conzett. This is particularly visible in his First Traversina bridge from 1996 in Graubünden [Fig. 4.7]. Here, a series of elements consisting of an articulated triangle are positioned on a line to form the passage of the bridge deck, which are connected as a system and contextualised through their formation of the whole to accommodate the span, the landings and the final structural expression. In the Swiss Pavilion from 2000 in Hanover, Conzett works with Peter Zumthor on a plan in which numerous simple wooden elements are added through stacking. The system of cross-layering the elements forms a simple assembly, as no displacement takes place, which nevertheless creates a deep, partially transparent and expressive reading of the entire formation when exposed to light and the movement of people.

The work of Uruguayan architect and engineer Eladio Dieste, particularly the Church of Christ the Worker [Fig. 4.8] from 1960 in Atlantida, most extraordinarily expresses the power of brickwork. Specifically, the undulating curves forming the walls and roof are achieved by the simple element of the brick through minor displacements in the wall, creating expressive structural formations. The organisational agility of the element can be seen in the similar Montevideo Shopping Center from 1988 in Montevideo, where the undulating walls are mirrored over a horizontal plane, allowing another expressive reading of the brickwork. (Anderson, 2004:163)

Lastly, the work of Japanese architect Kengo Kuma exemplifies the capacities by organisation of the simple element, in both the Yusuhara Wooden Bridge Museum and the GC Prostho Museum [Fig. 3.8], both from 2010. In the former, laminated veneer lumber members, as elements, are cross-layered with small insertions to fix the positions as a system. From a single point, the formation expands three-dimensionally to form the bridge by stacking the elements, with each layer overhanging the previous. In the latter, wooden sticks with a 60x60 mm cross section with varying lengths are brought together in the 'chidori' system (Frampton, 2012:190), allowing an infinite continuation of the assembly and thus extensive capacities in the process of creating formations. The depth and spatial expressiveness of the assembled and systemised elements allow a nuanced and articulated filtering of the light as environmental contextualisation.

The examples above indicate an architectural methodology, which is situated across continents in South Africa, Europe and Asia and applied to diverse architectural spatial programmes, such as bridges, museums, churches, concert halls and housing.

Figure 4.8

Church of Christ the Worker (1960) by Eladio Dieste showing the capacities of structural and expressive aspects when working with the simple brick geometry. Photo by Nicolas Barriola.

Behind or, perhaps more specifically, inside the Element, System, Formation instrumentality lie an idea and structure of organisational principles. Organisational theory, applied commonly to the description of structures within management and economic systems (Tryggestad & Georg 2011), may thus have something to offer in the elaboration and understanding of increased instrumentality of systems in architecture. Looking back to the notion of Peter Pearce, *'minimum inventory, maximum diversity'*, it can be suggested that the minimum inventory be paralleled to a standardisation of elements, effectively reducing its quantity to the element used, which then can be organised subsequently for the many, or, in short, *'standards are by definition rules for the many'* (Brunsson, Rasche, & Seidl, 2012:20). In the case of bricks with a very defined geometry, the possible constellations become tangible for the adopter of the standards. Due to its geometric organisation, it allows a multitude of configurations, which again illustrates a set of standards, not only for the brick itself, but also for the system of adding the bricks together as defined elements. The system-level standard in itself, therefore, benefits from the simplicity of the element-level standard. Restating the argument of increased adaptability:

> *The dynamics inherent in the adoption of standards result from the process through which those general rules become applied to specific organisations – or 'translated' into localised rules. (Brunsson, Rasche, & Seidl, 2012:21)*

This orientation may also serve to develop new integrated design proposals, as the conventional linear architectural model as a method for design is challenged by the increasing demands for information, project control and integration of diverse aspects in early design phases. (Schweber & Leiringer, 2012:490).

Architectural researcher Phil Ayres has proposed what he calls the *Persistent Model*, which perhaps should be considered more of a theoretical construct than an operational all-inclusive utility tool. It points to the notion of an architectural model that is not complete but in progression and, through this, open to influence (Ayres 2008). In this line we can point to the importance of a model's flexibility to be a continuum of actions, or actors in the broadest sense, which exert force on the project from which it progresses. Revisiting the Kingo Houses, the elements are related in a system of interconnection and dependence, providing a series of internal forces, while being influenced by contextual conditions, external forces. This in turn leads eventually to a formation by the relationships inherent in the system, the context and the maker agency, the latter inserted from Heidegger. From this process network of influencing actors, meaning appears to the maker for all three levels and the context.

One important point following from this line of reasoning is that artefacts, technology and even the materiality of a building can be regarded as entities actively involved in transforming, translating, modifying or even distorting the meaning that they are assumed to carry. (Tryggestad & Georg, 2011:184)

In opposition, it can be argued that the above approach constrains the development of custom and unique forms by being restricted to a system approach. However, the Kuwait National Assembly project illustrates an approach from which industrial connectivity and assembly methods between standard elements (modules) can be

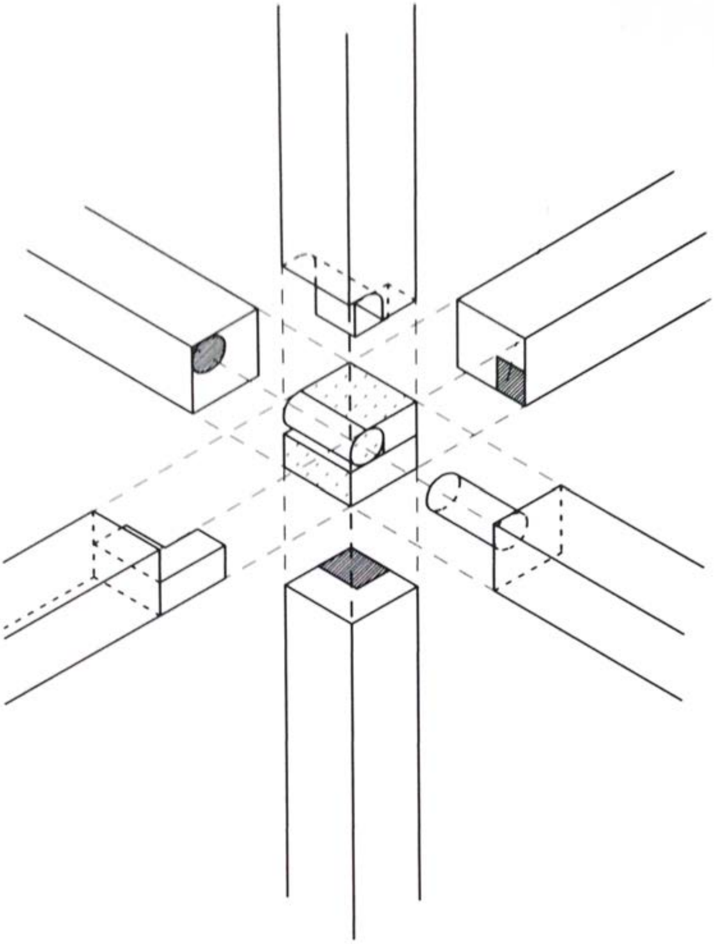


Figure 4.9

The Chidori assembly system for the GC Prostho Museum project by Kengo Kuma. Drawing from the book 'Kengo Kuma Complete Works', p. 190.

paired with unique and non-standard formal expression (courtyards). The instrumental methodology thus illustrates a potential approach to surpassing the problematic dichotomy between the unique and the mass-produced in architecture. Additionally, this points to the importance of elements being carefully created by the making agent for their ability to allow differentiation in time and space, while being organised in a greater system of similarity and connectivity.

The aspect of differentiation and unity can be approached through geometry, as particularly shown in the Kuwait National Assembly, and in part in the associated cases. What is evident, however, is an absence of the material behavioural integration from an environmental perspective. This argument is also visible in the statement above by Vallhonrat, criticising the lack of reading of material behaviour in current architectural production. In turn, the causa materialis, in relation to transformative influences induced by the environment, is significantly omitted. By orienting tectonics towards the matter aspect of techné, causa materialis, a potential advancement of the current approach to tectonics in architecture may lie in an inclusive set of environmental forces and their time-based architectural articulation.

By acknowledging an increased orientation towards material agency and the impact of environmental agency during the design methodology, as suggested above, including the arguments provided in the previous chapter, the question below is formulated.

How can we integrate and instrumentalise an extended material and environmental agency towards a more complete integration of the four causalities into Environmental Tectonics?

4.3 Transformation

In this section, the transformative processes that result from the interaction between environmental agency and material agency are examined. The section expands on the cases and arguments pursued in the previous chapter, now with the aim of illustrating the inherent making capacities as related to causa materialis. Thus, the section extends the theoretical suggestions presented above, but with a more direct relationship to the matter behavioural processes of architecture. In the material and environmental domains, the cases are first studied at the micro-scale, focusing on the structural and environmental mechanics at the level of material molecular organisation. The underlying matrix relating the examples below to each other is structural modification and its causalities over time, as previously stated by Williams (Williams 1995). The first cases below, Wood, Metal and Stone, focus on material transformation on the molecular level with implications on a building scale, while the other cases, Brickwork and Half-timbering, connect directly to the formation of geometric organisations as illustrated in the previous section.

Figure 4.10

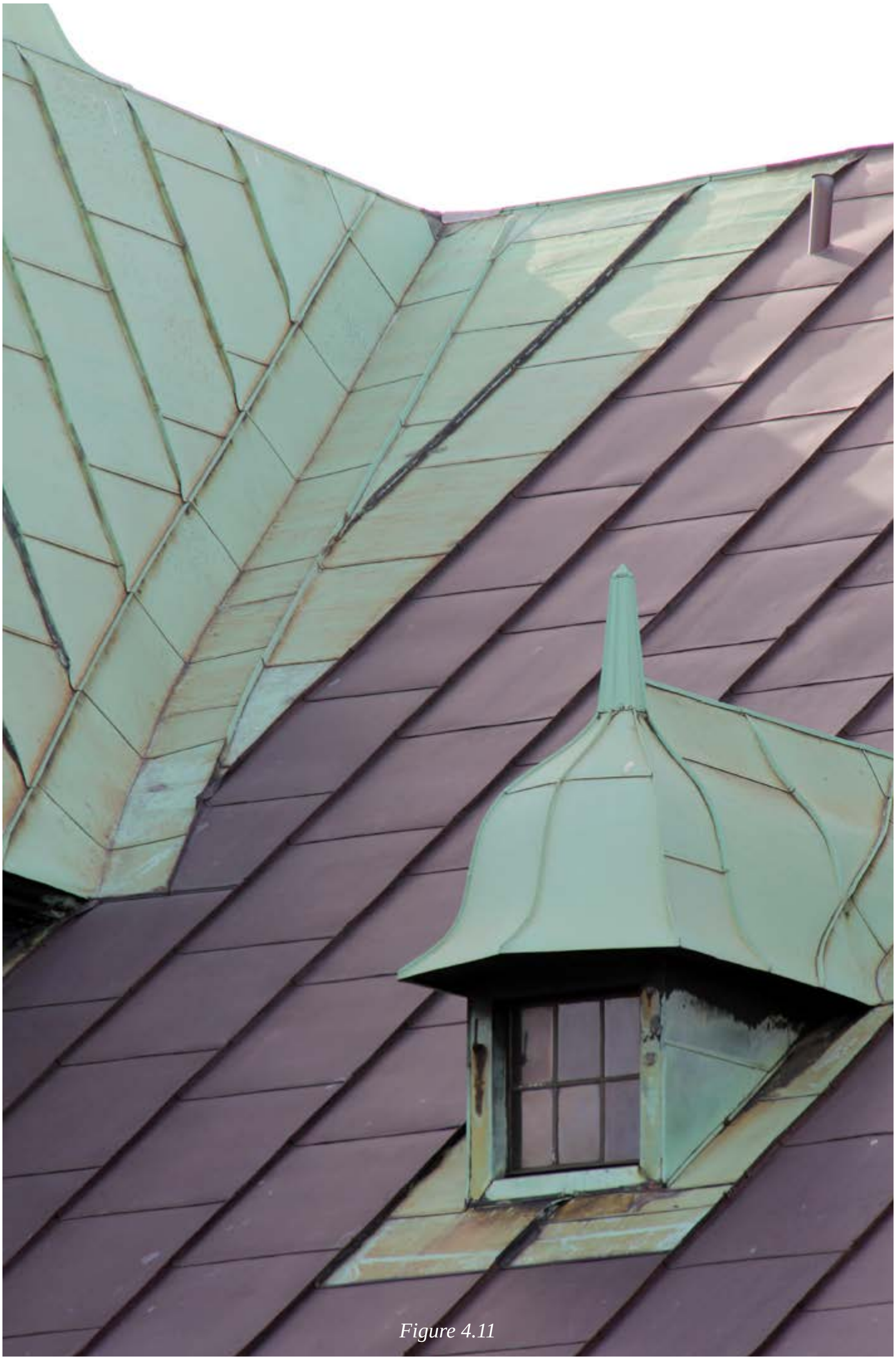
Detail view of AHO Pavilion at Oslo Architectural Triennial (2010) Responsive Wood Studio, Wing Yi Hui and Lap Ming Wong. Photo by Lap Ming Wong.

Wood

Recently, wood has reappeared as a favoured material of investigation by architectural researchers. This is partly due to the growing interest in the anisotropic material properties of the wooden fibre organisation as produced by natural growth processes. [Fig. 4.10] By layering fibres, wood obtains differentiated structural capacities that can be exploited in situations where structural non-uniformity is desired. This differentiated structural material organisation has been paired with another property of wood, namely its hygroscopic properties, allowing wooden surfaces to bend according to their specific fibrous makeup. This ability has been explored for a responsive architecture from the early studies of Michael U. Hensel and Achim Menges (Hensel & Menges 2006; Hensel et al. 2010; Hensel 2010) via Steffen Reichert (Menges & Reichert 2012) to many others exploring many similar setups and behaviours as the original studies. While the above has emphasised the abilities of a responsive behaviour by material performance, discussed in the thesis Introduction, it is here the intent to use the studies as examples of the deep relationship between environment and perceived constructs. The basis for wood's hygroscopic properties is its ability to absorb and release the humidity of any environment. This, as has been studied by the aforementioned researchers, results in bending behaviour if the moisture content is above or below the fibre saturation point within the wooden cells. Another reason for bending or warping is the asymmetrical release of moisture from the cells. Humidity, what we perceive as environment, becomes the determinant factor of the wooden surface's bending composition. Hence, both visual articulation and practical enclosure function as presented in the aforementioned studies, and are explicitly dependent upon and interconnected with their local climatic environment for actualisation as an architectural construct. The transformation of these constructs is immediate, with bending actuation happening over a time period measured in seconds. Furthermore, this form of material-environment interrelation is of elastic character, to the point where the wooden cells cannot obtain or release more moisture from and to the environment.

Metal

In the case of metals, copper is used as an example of metallic transformation in architecture. Copper as a case is relevant due to its evident presence in architecture historically and with broad applications, from housing to cathedrals (Anon 2011). What is of particular interest to this work is the cause of the transformation that copper undergoes during its application in architecture. When installed, copper is commonly brown and polished, resulting in a shiny surface. In climates with precipitation and coastal areas, the surface becomes mat within weeks, and continues to transform from black to light green over a few decades depending on local climatic conditions [Fig. 4.11]. The process of oxidation is a chemical reaction between the copper molecules and the acid of the environment, altering the outer surface layer's chemical makeup from copper through cuprite to brochantite (Krätschmer et al. 2002; He 2002; FitzGerald et



Brochantite oxidation of 'older' copper parts at Børsen (Copenhagen Stock Exchange) illustrating the transfer from brown to light green surfaces. Photo by Isak Worre Foged.

al. 2006). Cuprite is the first layer that is formed, changing the appearance to black, with brochantite only forming in humid conditions, creating the known light green patina. Beyond the visual material-environment interdependencies of copper, another aspect of its cause and effect can be suggested. When the surface transforms its colour appearance, it also transforms its emissivity properties, meaning its ability to absorb and reflect energy, based on the black-body theory of emitting bodies by the German theoretical physicist Max Planck. As the colour undergoes transformation, emissivity will increase, enabling the surface to absorb more energy. A simple simulation setup is created with six panels of 1 m^2, three as brown shiny copper, three as light mat green copper. Each group of three is angled at 30, 60 and 90 degrees to the sun vector, enabling comparative analysis between the simulated specimens. If measured during simulation, that is, the equinox in Copenhagen, one can observe that the capacities for the material-environment interrelation have consequences for the capacity of architectural bodies to receive or reflect energy according to material-environment organisation. When copper reaches a light, green and mat surface, it absorbs four times more irradiance than the previous brown, polished surface. This process is normally not reversible, as the climatic environment simply continues oxidation, resulting in a plastic, constant, modification of the material makeup.

Stone

In the extensive geomorphological survey by Turkington and Paradise (Turkington & Paradise 2005), it is illustrated through a century of research into sandstone that materials for massive building foundations are influenced by environmental forces, inflicting perceivable change over time. Notably, the formations of stone constructs are in visible spatial forms, different from the formations of copper, which by visual perception only changes surface characteristics. The complete complexity of sandstone erosion is still to be understood, but a combination of moist, running water and the growth of crystals is evidently an active material-environmental agent in the occurring morphological modifications. These processes have a significant impact on the visual expression of buildings constructed in sandstone, as is the case with many European institutional buildings and housing structures in the Mediterranean area, which have been standing for centuries. Subtractive processes of the sandstone construct form a large variety of surface articulations, such as Tofoni structures [Fig. 4.12 and 4.13], which are characterised by honeycomb formations that in themselves become associated with the material by reading the material properties of resistance and durability through their transformations. Laboratory and field studies illustrate that the transformative character can be related to the density of the material itself and the orientation towards the sun. This impacts the processes, as moist surfaces will dry faster due to evaporation, reducing water run-off processes. Additionally, one must consider the factor of actual building run-off parts, moving running water away from the surfaces and therefore also reducing depositions of salt crystals that otherwise exercise pressure inside the sandstone, enforcing ruptures (Sancho et al. 2003; Gómez-Heras et al. 2006; Turkington & Paradise 2005). These transformative

Figure 4.12

Sandstone erosion process at housing unit in Valetta, Malta showing the transformation by material-environmental interactions. Photo by Isak Worre Foged.

processes can be understood through both positive and negative perspectives, in that with time, erosion will become critical to the point of structural failure, or, conversely, as argued above, erosion increases our ability to read and understand the material properties as a measure of a building's lifetime and its relation to its climatic context. Architectural theorists David Leatherbarrow and Mohsen Mostafavi elaborated upon the process of subtraction induced by weathering as follows:

> *Paradoxically, weathering produces something already there by subtraction. This exchanges the roles of art and nature. In design, art is assumed to be the power or agency that forms nature; in the life or time of a construction, however, nature re-forms the finished art work. (Mostafavi & Leatherbarrow, 1993:64)*

Following the four causes taxonomy, knowing the material and its transformation and form, a small study to understand its effect on thermal regulation by its transformation is conducted. An examination by three-dimensional scan of an eroded sandstone façade segment exposed to the sun is carried out. This is followed by a thermal analysis detecting the relative difference in accumulation of irradiance over a year between a flat and an eroded façade, both in Copenhagen. While the stone surface significantly increases, under transformation, its surface-area potential for energy absorption, it considerably decreases, in contrast, the capacity of receiving solar energy. The transformed surface has an irradiance per surface area unit of 5.8 times lower in the winter period and 4.7 times lower in the summer period. Rather than improving its ability to heat the boundary layer of the building, it improves its ability as a cooling capacity for the building envelope. This represents a potential strategy for warm climates.

Brickwork and Half-timbering

While all processes of transformation are under some impact from gravity, which has manifested itself in the theoretical orientation of tectonics as laid out in the beginning of this chapter, the cases above illustrate architectures that are primarily affected by other directional and temporal actors of influence. The cause and effect is located at the molecular level of modification, with transformation characteristics at the level commonly perceived in architecture. Following is an examination of a transformational process on a scale more familiar to architecture. With a construction history dating more than a millennium back, brickwork is the best surviving architectural material system in use today. Its simple geometry has resulted in a multitude of constellations across nations, with a revived and growing interest in Northern European countries (Jensen 2008) due to its inherent properties of durability, expressive character and vast possibilities of configurations. What is of particular interest here is its significant capacity to transform the configuration of elements in near-neighbour relationships to accommodate large transformations of an overall surface [Fig. 4.14]. From a technical engineering perspective, studies of both physical experiments and simulated

Figure 4.13

Similar process of sandstone erosion process at Børsen in Copenhagen. Photo by Isak Worre Foged.

experiments have been conducted to understand and calculate the shear and stiffness forces at place in these assemblies (Bosiljkov et al. 2005; Brasile et al. 2010; Salerno et al. 2001; Brooks 1990) with the objective of predicting possible lines of breakage. While these studies give good insight into the force actions, they reveal less about architectural transformation in the perspective of expressive articulation resulting from these processes and how one can understand the construct-environment relationships. The German engineer and architect Frei Otto published in his book *Finding Form* (Otto & Rasch 1996) a series of studies in which he stacked small assemblies of bricks without a binder in a circular organisation. The bricks were positioned on a planar plate, which could be increasingly sloped to enforce deformation and rupture. The studies remain limited and very laboratory-based in character, but nevertheless illustrate the dynamic and somewhat new organisations of form and entities exposed to force modifications.

When observing beyond simulated and laboratory models of brickwork transformation, one sees in many larger Northern European cities the transformative capacities of such material assemblies as [Fig. 4.14]. A change in foundation or a change in neighbouring buildings' lateral support has resulted in a force modification across the façade. With the window as a measure of perceived deformation, it is possible to detect the effect of scale in relation to the elements. The individual bricks remain in their original geometric form, while the window and wall segment as a whole undergoes radical deformation. This suggests that the binding together with the proportion and scale of the brick allows these transformations as a system, and not as adaptation of the individual entities, as can be argued is the process in the aforementioned cases. What it clearly illustrates is the much-referenced sentence in architectural research related to adaptive procedures by the famous mathematical biologist D'Arcy Wentworth Thompson.

> *The form, then, of any portion of matter, whether it be living or dead, and the changes of form that are apparent in its growth, may in all cases alike be described as due to the action of force. In short, the form of an object is a diagram of forces. (Thompson 1992)*

While apparent in natural systems and, as has been argued, in architectural systems, it implicitly illustrates an adaptation to changed conditions. In architectural theory, this form of translation could have other meanings, which may influence the architecture's capacity to endure. As the transformation of the wall takes place, it ties itself to the location, as it is the forces at work in situ from which the architectural characteristics are formed. Considering the notion of '*structural ornament*' and '*ornamented structure*', as described by Frampton (Frampton 1983), ornamentation in this process is embodied by structural-material transformation. This in turn may suggest a temporal increasing Environmental Tectonic articulation due to the advancing transformation over time.

A related example is the case of half-timbering. While masonry structures are aggregated systems of identical elements, half-timbering is a composite of a timber framework with masonry infill, positioned traditionally on a stone foundation.

Brick wall deformation in Copenhagen to the degree of enforcing significant geometric displacement of the window frame. Photo by Isak Worre Foged.

This composite construction has shown the same capacity as masonry structures, withstanding major deformations from its initially constructed vertical plane, allowing very local deformation across an entire surface leaning inward and outward within the same wall segment [Fig. 4.15]. In pure brickwork constructs, the individual bricks' displacement from the neighbouring brick is possible, enabling the overall transformation, while in half-timbering, the straight vertical members of the wooden framework seems to be deformed as a three-dimensional skeleton undergoing transformation as a bar-linkage system. This is enabled by some rotational ability in otherwise moment-fixed joints. Due to its composite structure, half-timbering, despite its deformations, is known to be exceedingly resistant to structural failure under extreme conditions such as seismic activity (Vasconcelos et al. 2011), supporting the notion of an architecture that responds and transforms with a multitude of acting forces.

As the above examples illustrate, the environmentally induced transformations of common building materials and construction systems, with responding behaviour perceivable from seconds to centuries, suggest an extended causa materialis in tectonics. Furthermore, Leatherbarrow posited that responsiveness does not necessitate visual perception of change, but can be bound by the reactive forces constantly at play (Leatherbarrow 2009).

From the previous statements made above by Semper, Goethe and more, from Hvattum, the relationship of architecture to autonomy and referentiality can be reiterated here. An approach of imitation by reference, for instance by applying natural motives as ornamentation to architecture, is often used.

However, in the cases above, ornamentation appears from the structural articulation and process of its making in both pre- and post-constructed conditions, by design method and post-construction material transformations. Intended transformations as a method for time-based articulation of ornamentation can therefore be suggested to extend the Environmental Tectonic quality of a given work. Due to wear and tear, matter relationships become more transparent and readable over time. The transformation therefore speaks about both the architecture and the environment in connection. It is thus disassociated from architectural agendas that employ organic forms as motive and formal expression, as can be seen from the Art Nouveau movement to contemporary Biomorphic expressions. Along these lines, Mostafavi and Leatherbarrow posited the following:

> *This differs from the imitation of organic forms in architecture, in art nouveau buildings for example, insofar as these buildings attempt to look like natural elements, whereas surface modification results from the action of these elements. (Mostafavi & Leatherbarrow, 1993:69)*

And:

> *In the time after construction, buildings take on the qualities of the place wherein they are sited, their colours, and surface textures being modified by and in turn modifying those of the surrounding landscape. (Mostafavi & Leatherbarrow, 1993:72)*

Half-timbering house at Frilandsmuseet, Denmark, illustrating the capacity of the material make-up to undergo significant deformations while remaining functional. Photo by Isak Worre Foged.

This points to the statements provided in the previous chapter, in which architecture can be constructed by weather. It also points to the origin of tectonics through techné, in an explicit relationship with the four causalities that can be detected as these transformations embody the material, the form, the relationships and the effect in a continuous process of appearance. Mostafavi and Leatherbarrow stated that such processes indeed make architecture locally manifested.

> *Generally speaking, whatever controls the action of the weather is referred to as the 'weathering' – one word naming both the process and the object through which this process is controlled and allowed to make itself manifest. (Mostafavi & Leatherbarrow, 1993:36)*

Architecture is, quite obviously, not autonomous, as it is engaged in persistent and interlocking relationships with the forces at work in the world. Furthermore, it can be suggested that architecture, as defined by Environmental Tectonics, is not an imitative field based on referentiality to nature. The reasoning behind this statement is that architecture is influenced by the same forces as the forms of plants and animals used for imitation, thus removing architectural articulation from its direct influencing forces to objects that are shaped by the same forces but under different conditions. After all, a plant or an animal is literally not a building, or a bridge. By basing architecture on referentiality to natural forms, the four causes of techné are lost, as the interrelated aspects of material, form, relation and effect are disconnected from the forces at work related to architectural making.

With the identification of a tectonic agenda oriented towards influence from environmental processes, and the description of instrumental procedures, by the schematic organisation of element, system and formation, the question arises as to where the instrumentality and transformations are most relevant in architecture in relation to the aspects of human-oriented environmentally sustainable constructions.

4.4 Membrane

From Semper, we inherit the four elements of architecture, earthwork, hearth, framework and infill wall. In the positioning of these as tectonics and stereotomic, they are loaded with meaning in that they, according to Semper, can be classified as more or less true to their functioning. Frampton addresses this ordering of the elements as he states:

> *The concept of layered transitional space as it appears in traditional Japanese architecture may be related indirectly to the distinction that Semper draws between the Symbolic and the Technical aspects of construction, a distinction that I have attempted to relate to the Representational and the Ontological aspects of tectonic form: the difference, that is, between the skin that re-presents the composite character of the construction and the core of a building that is simultaneously both its fundamental structure and its substance. This*

> *difference finds a more articulated reflection in the distinction that Semper draws between the ontological nature of the earthwork, frame and roof and the more representational, symbolic nature of the hearth and the infill wall. In my view, the dichotomy must be constantly rearticulated in the creation of architectural form, since each building type, technique, topography and temporal circumstance brings about a different cultural condition.*
> *(Frampton, 1995:16)*

Frampton imposes criticism on the stringent proposition of division of what is ontological, the nature of what something is, and what is re-presentational, that is, what it points to. It is perceived as 'true' that the earthwork and the framing directly illustrate the load-bearing system. However, as has been shown with the nature of environmental forces within this and the previous chapter, Environments, the boundary of a building, with its deep and complex organisation, is to the same degree exposed to influencing aspects pointing directly back to the ontological nature of its construct as much as to the framing structure. Furthermore, the infill wall, or membrane, as an architectural element, is often continued topologically as roof, for instance, by folding (Lynn & Carpo 2004) with the roof classified together with the framing and earthwork. Hence, the taxonomy of the four elements of architecture becomes increasingly blurred, thus suggesting a change not only in the classification of elements in ontological and representational categories, but also in the understanding and positioning of the membrane in architecture.

As outlined above, current climate and energy research illustrates the necessity of establishing the building membrane as a responsive architecture to meet contemporary and future energy demands of buildings as advocated by the Danish government (Winther 2013; Winther et al. 2009). While these demands are local demands, they appear to become general conditions to be met in response to energy use in the built environment while also bearing in mind internationally politically established goals.

And, with the focus on an environmentally oriented architecture and the extended dimension from a representational or symbolic element to an ontological and multi-faceted element of architecture, the tectonics of the membrane become increasingly necessary to address.

In her analysis of the Alexandria Library competition proposal by Alison and Peter Smithson, Anne Beim (Beim, 2004:157) points to the building envelope as a layered skin with the ability to respond to thermal aspects. It lies in the description of the proposed building that the design embodies a form of sensitivity to its environment through its tectonic make-up, by the use of operable louvers for the circulation of air in relation to the movement of air on the site. This form of material organisation exhibits the potential ability to make the building respond and interact with the environment by changing its visual and airflow permeability, expressed metaphorically as being like the skin of humans. Such an approach is strongly related to the idea of Free Running Buildings.

In a similar, more theoretical radical position, Kenneth Frampton (Frampton 2011) points to the original 1926 publication of Siegfried Ebeling, with the title *Space as Membrane*. In this treatise, Ebeling inserts a series of objectives and positions in relation to a future and more biologically oriented responsive architectural construct than the predominant agenda of the flat facade style and functioning of Modernism. His position is in opposition to his own intellectual Bauhaus platform, and a separation of the, in his mind, reductive idea of ‘architecture as a machine’ (Scheiffele, 2010:iv). Strikingly for the time and still directly relevant, Ebeling argues for a broader architectural approach than the prevailing technological agenda he criticises:

> *The choice of building material should be geared exclusively towards achieving a dynamic functioning of the facility as a whole – something that has to become more and more a shared object of investigation for biology and physiology on the one hand, and physics and chemistry on the other. (Ebeling, 2010:31)*

He elaborates distinctively and outlines central aspects investigated in this work, with the emphasis on reciprocal interconnections of space and structure as illustrated in the section Transformation and in large parts of the previous chapter.

> *The proportions of a space, the materials of a wall, the pressure and composition of the air, temperature and degree of luminosity, are all values that are dependent on each other, with ‘radiation’ being the common denominator. Added together, however, they would not yet result in what the organism experiences as spatial tension (absorbed by the senses, as a series of tonal vibrations). What is needed is progressive, systemic research aimed at constructing an apparatus that could gauge the radiation (including light and acoustic ratios as well as spatial proportions) of any interior space and create comparative values based on an optimum value. On the whole it should be stressed that the house is to be perceived as a conducting medium (Durchgangsmedium) channelling a continuous stream of forces – a stream of forces that is refracted several times in its trajectory, flowing from a ground surface that in geophysical terms is variously defined, through a hollow space, to an open space that is also variably defined, and then back again in the reverse direction. In the centre of this play of forces, in each instance, are organisms subject to both physiological and psychological laws. (Ebeling, 2010:33)*

Written in 1926, almost 90 years ago, contemporary environmental architectural research is only now about to catch up to his argument of combined physiological and psychological measures in current understandings of the well-being of the human organism in architecture. While cultivated in the terminology used by Ludwig Mies van der Rohe, Walter Gropius and Le Corbusier, words such as ‘apparatus’, somewhat evolved from machine, survive. But he advances by aligning space with membrane, rather than positioning the membrane as a dividing construct, and therefore affiliates the notion of the architectural envelope with the descriptions of natural systems boundary layers by Oke (Oke 1987) et al. Thus, his notion of membrane, which in this thesis is interchangeably used with envelope, is much more open to explorations, understandings and its articulation in architecture. To address the architectural

Figure 4.16

The inside storage space of the Gantenbein Vineyard, Switzerland, illustrating the envelope's capacity to modulate environmental aspects of light and, though it cannot be seen, the thermal regulation. Photo by Ralph Feiner.

envelope from an applied perspective, below is an examination of a contemporary designed and built envelope, which is thematically related to prior cases.

Brick membrane

In the façade design of the Gantenbein Vineyard in Fläsch [Fig. 4.16], Switzerland from 2006, the architects Gramazio and Kohler explore the aforementioned capacities of the simple element, brick, in a system, allowing for multi-levelled architectural formations of core functionality and symbolic representation. The organisation of bricks as a permeable architectural membrane has a clear environmental-spatial objective of creating the best conditions for the maturing of grapes for wine production. They stated:

> *The initial design proposed a simple concrete skeleton filled with bricks: The masonry acts as a temperature buffer, as well filtering the sunlight for the fermentation room behind it. The bricks are offset so that daylight penetrates the hall through the gaps between the bricks. Direct sunlight, which would have a detrimental effect on the fermentation, is however excluded. (Gramazio & Kohler 2014)*

The complexity sought from the organisation of bricks expands as the array of bricks come together to form a symbolic motive of grapes in a basket, only readable from afar. This proposes a reading from different distances, and by different sensations: visual, tactile and thermal, exclusively perceived according to the position of the human. In the case of bonding the elements together, glue has been used, allowing the bricks to be placed with minimum distance, compared to masonry with mortar. This suggests an immediate reading of the individual bricks and their formations as a whole. However, this can only be achieved in a planar segment of machine-produced bricks, as the geometry of the elements must be absolutely rectilinear. The system of organising the elements is thus fixed to rotating the bricks in a horizontal plane or through other forms of stacking. In spite of this, the architectural membrane is an innovative use of brick layering technique combined with a conventional understanding of the material properties. From this, it can be suggested that materiality, joinery, system and formation are key elements that are all investigated holistically and that, during design conception, can be freely re-composed and re-understood. Hence, the appearance of the aspects at work is directly accessible to the making agent, supporting an articulation of both core functionality and expressive visual effect simultaneously.

In Ebeling's time, the predominant thinking on forces in relation to architecture was and, as is outlined above, still is that of gravity. Nevertheless, his statement below regarding what frictions are and the interplay that might occur to bring about a higher environmental articulation in architecture is profoundly more nuanced. He posited:

> *In a world where things and experiences are fantastically mutable the house*

remains a relatively rigid, multi-celled spatial entity. Its base is either fixed or loosely connected to the ground through which manifold forces flow. Its remaining surfaces come into contact with the thinner medium that is penetrated by rays of light of variable quality, alternating periodically. The friction between these two sets of forces plays out in the hollow space of the house, entering into a low-governed interaction – mental and physiological – with the inhabitants inside. The degree of harmonious balance between these tree components determines the character and quality of the architecture. (Ebeling, 2010:8)

As relevant today as it was then, it is possible to adopt the environmental force frictions and extend the integration of aspects towards Environmental Tectonics. Ebeling's thoughts on these forces are applied to both design processes and post-construction processes. This positions his ideas of architecture as a much more time-based and continuously unfolded making, appearance, rather than the construct of generic and fixed artefacts isolated from their context. This is particularly evident when Ebeling is elaborating upon architectural membranes. In partial opposition to a wide integration of aspects, Danish engineer and founder of ARUP, Ove Arup, stated that the integration of a multitude of aspects has consequences for the expressive articulation of the forces, and thus for the reading and appearance by making.

Moreover, the 'organic' shape is only correct for a particular set of forces. If the wind blows from the other direction, or the maximum load occurs in the next bay, the shape should really be different to be effective. The right shape is therefore one which 'envelops' all the organic shapes appropriate to the varying conditions, and this is not likely to be nearly so interesting. (Arup, 2012:40 [1954])

This reinserts the notion of the 'truth' and 'honesty' of architectural structures, as embedded in the notion of tectonics. We return to Heidegger as he posits:

But how does bringing-forth happen, be it in nature or in handwork and art? What is the bringing-forth in which the fourfold way of occasioning plays? Occasioning has to do with the presencing [Anwesen] of that which at any given time comes to appearance in bringing-forth. Bringing-forth brings hither out of concealment forth into unconcealment. Bringing-forth comes to pass only insofar as something concealed comes into unconcealment. This coming rests and moves freely within what we call revealing [das Entbergen]. The Greeks have the word aletheia for revealing. The Romans translate this with veritas. We say 'truth' and usually understand it as the correctness of an idea. (Heidegger, 1977:5)

The problem of integrating multiple aspects is thus twofold, both if something is true or not, and whether one can perceive this in architecture. One can ask: does an aspect need to be revealed more than other aspects in order to allow a reading of appearance? And if so, what should that be?

Jane Darke, a researcher of design processes, specifically studies those regarded as excellent designers and has studied how they approach their work. The conclusion of her work, which has been adopted by several leading researchers within the field (Cross 2004; Lawson 2006), is that the designer utilises what she refers to as ‘primary generators’ (Darke 1979). A primary generator can be a geometric figure, a principle or anything else that can be clearly converted to form. An example, one used by both Darke and others, is the Spanish architect and engineer Santiago Calatrava. Calatrava typically uses a well-defined geometric figure, as also seen in his many sculptures, which becomes the central departure for all other aspects. As aspects are added to and removed from a project, the central idea, principle or geometric figure is modified, though it is discernibly maintained. Interestingly, this echoes the notion of the Semperian Stoffwechsel and the Element, System, Formation methodology by the articulation of simple elements organised in a system, which, by influencing inner and outer factors, new aspects, and the making agent, constructs environmental architectural formations.

4.5 Synthesis, Conclusions and Propositions

In moving towards an Environmental Tectonic approach to environmentally sustainable architecture, an initial revisiting of the theoretical foundation of tectonics has been pursued. From this analysis, it is suggested that the original notion of techné, as elaborated upon by Heidegger, is explicitly connected to a framework that is based on environmental aspects. This is claimed to be the case, as it reveals not only the nature of the gravity-based construct or the articulation of a meeting between solid building parts, but also the intrinsic relationship between the material and the climatic environment. The meaning of the tectonic joint between parts becomes, in turn, a new notion of jointing between matter in different phase states, just as in the meeting between two solids. This is evident in the section on Transformation in the cases of copper, wood and sandstone, where the articulation of a visual expression is created from subtle environmental influences. The meeting of moisture with wood, acid with copper and salt with sandstone becomes the environmental tectonic joint between matter constituents. In this way, it illustrates the dynamic relationships and appearances between these agents and increases the local specificity through persistent construction processes.

In the section Addition, a prescribed architectural design methodology is elaborated. This is based on case studies that subsequently illustrate the Element, System, Formation approach and its general application across architects, projects and locations. It was argued that this approach allows greater design manoeuvrability, in turn enabling both environmental and structural aspects to be integrated in early design phases. Both arguments provided in the sections of Addition and Transformation are related to the Semperian notion of Stoffwechsel. From this, progressive processes permit appearance to become discernible throughout both the design process and the continuous construction process as particularly specified in the section of Transformation.

The approach of Environmental Tectonics does not contradict the established notions on tectonics, but suggestively extends and repositions its description and objective. Additionally, it is believed that an Environmental Tectonics agenda's abilities to support the four causalities in architecture are significantly increased, as its objectives and proposed instrumentality are extrinsically linked to people, matter, place and time. From this, a set of propositions positioning and adding to the proposition from the previous chapter can be formulated.

Proposition 3
Tectonics is based on four causalities

Environmental Tectonics is not an architecture of reference or of autonomy. It is an architecture situated by the four interrelated causalities inherent in the Heideggerian notion of techné towards poeises, which emphasises the inherent matter properties, the form appearing, the relationships between the form and the effect - the four causes.

Proposition 4
Maximum Structures

A compound of aspects and forces influences environmental tectonics, suggesting a notion of 'maximum structures'. When gravity is a tectonic focal point, the articulation of structures inclines towards 'minimum structures' based on structural efficiency and its related expression. Thus, Environmental Tectonics aims, in contrast, to capture the inclusive yet environmentally distinctive articulation.

Proposition 5
Semperian Stoffwechsel

Environmental Tectonics relies on the notion of Semperian Stoffwechsel, which emphasises the discernibility of a composite architecture through its transformative processes, at all times of design evolution. Thus, Environmental Tectonics is determined by its process of appearance at any point in time.

Proposition 6
Environmental Authorship

Environmental Tectonics acknowledges the environment as a making agent on equal terms to the human maker, allowing the authorship of architecture to be situated across time and across multiple agencies. This enforces the dynamic, and potentially unforeseen, environmental events occurring in the formation of architecture, rather than the intent to isolate architecture from its ongoing transformative potential.

5

Computation

5.0 Preliminary

In the Introduction chapter, several computational terms were used without further elaboration, such as 'search algorithms' and 'cellular automata systems'. In the following chapters, Environments and Tectonics, methods were proposed to perceive and assess an environment and to create construction methods from additive and transformational processes. These implicitly suggested computational procedures. In this chapter, Computation, the notions used previously are extended and developed based on the integration of computational methods in general and as a basis for specific methods in the formulation of Environmental Tectonics using the previous propositions. The initial questions, posed within the Introduction and restated below, were partially addressed in previous chapters. This chapter attempts to deliver a more explicit answer to the question:

What theoretical and instrumental assessment and environmental open-development models are needed to evaluate and evolve an environmental architecture? (Q3)

Further, it is intended to make propositions and answers to the extended questions:

What computational methods allow the integration and active influence of environmental aspects on architectural making? (Q8)

And:

What computational methods support the theoretical orientation of Environmental Tectonics as an agenda for a sustainable architecture? (Q9)

Following the methodology of etymological grounding, the chapter begins with discussing computational notions that construct the platform from which we can suggest methods and models for an Environmental Tectonics approach. While the first section may appear to be of a historical character, it attempts to illustrate the notion that computation was, in its infancy, occupied with similar issues to those pursued in this thesis, though for different reasons. This section is followed by the two computational orientations of Machine-based computation and Material-based computation, relating the previous propositions to computation. To integrate and further advance these computational methods, Hybrid computational models are suggested. These are based upon related work in other scientific fields and are pursued to address the objective of the thesis and the questions that have arisen throughout the dissertation. Based on these discussions, an additional set of propositions is formulated as the basis for design research experiments.

5.1 Notes on Computation

In 1928, mathematician David Hilbert formulated the *Entscheidungsproblem*, or 'decision-taking problem', which asks for a system or procedure that can construct an answer, 'yes' or 'no', to a mathematical problem of first-order logic, based upon an axiom question. This problem formulation follows the work of mathematician Gottfried Leibniz, who sought a system or machine that could manipulate symbols to determine truth-values of mathematical statements (Davis 2000). Previous computational machines were constructed based on complex mechanical systems that automated and optimised registration and ordering of telecommunication and infrastructural systems, such as the design of the *Difference Machine* in 1822 by Charles Babbage (Collier 1970). However, it was not before the conceptual construct of the *Turing Machine* by mathematician, logician, cryptologist and computer scientist Alan Turing that a formalisation for the contemporary computational machine could be developed.

Turing Machine

The Turing Machine is a conceptual blueprint of a model that can compute computable natural decimal numbers (Turing 1936). The concept of this machine is based on the combination of two elements, a 'tape' and a 'machine' that perform the operations 'scan', 'erase' and 'print'. Turing provides a clear description of the conceptual setup and platform to create a process in which computation of decimal numbers can be performed. Turing stated:

> *We may compare a man in the process of computing a real number to a machine which is only capable of a finite number of conditions q1, q2, ..., qR which will be called 'm-configurations'. The machine is supplied with a 'tape', (the analogue of paper) running through it, and divided into sections (called 'squares') each capable of bearing a 'symbol'. At any moment there is just one square, say the r-th, bearing the symbol S(r) which is 'in the machine'. We may call this square the 'scanned square'. The symbol on the scanned square may be called the 'scanned symbol'. The 'scanned symbol' is the only one of which the machine is, so to speak, 'directly aware'. However, by altering its m-configuration the machine can effectively remember some of the symbols which it has 'seen' (scanned) previously. The possible behaviour of the machine at any moment is determined by the m-configuration qn and the scanned symbol S(r). This pair qn, S(r) will be called the 'configuration': thus the configuration determines the possible behaviour of the machine. In some of the configurations in which the scanned square is blank (i.e. bears no symbol) the machine writes down a new symbol on the scanned square: in other configurations it erases the scanned symbol. The machine may also change the square which is being scanned, but only by shifting it one place to right or 1eft. In addition to any of these operations the m-configuration may be changed. Some of the symbols written down will form the sequence of figures*

> *which is the decimal of the real number which is being computed. The others are just rough notes to 'assist the memory'. It will only be these rough notes which will be liable to erasure. (Turing, 1936:2)*

The machine operates with a simple notation of '0' and '1', binary strings. These symbols, when scanned, erased and printed, combine to form a set of operations that lies at the core of computational logics. The configuration of the symbols (place and value) determines the behaviour of the machine and the final computation. The process of computation is, in the Turing Machine, a series of sequential operations whose capacities are further elaborated upon in the Church-Turing Thesis.

Church-Turing Thesis

Parallel to the work of Alan Turing, Alonzo Church (Turing's doctoral supervisor) developed his thesis on the 'effective calculability' based on recursion, which is, in mathematics, a repeated application, a theoretical idea that was made possible in the conceptual framework of the Turing Machine. Expanding on this idea, the thesis says that *'The notion of an effectively calculable function from natural numbers to natural numbers should be identified with that of a recursive function'* (Church 1936)(Blass & Gurevich 2003).

In brief, this applies the notion of sequential operations, recursive operations and, thus, time as a factor, through a series of discrete steps performed by the machine. While abstract, the conceptual construct of the Turing Machine and the Church-Turing Thesis is a significant manoeuvre in defining the basis for computation through the clear separation of a physical machine and software that combine to perform computation. In extension, both the Turing Machine and the Church-Turing Thesis serve as a universal construct for computation, and thus was born the notion of the Universal Turing Machine (UTM).

Of importance to the idea of environmental constructions are the remarks by Turing in his 1948 and 1950 papers (Hodges, 2004:10) that computational actions through program modifications can move beyond mechanical operations to that of initiate operations and thus the program could move on to perform operations beyond the foreseen actions of the programmer (Hodges, 2004:6). This argument separates the idea of computation further from the previous mechanical constructs, as it allows adaptation beyond an initial descriptive state. One consequence is a separation between hardware and software.

Extended concepts and models

A general understanding and experimental evidence of the functioning of the Church-Turing Thesis in relation to computation is evident. That, however, as Blass and Gurevich explained, is not identical to that no developments to the computability of algorithms have been conceptually formulated and created since (Blass & Gurevich 2003).

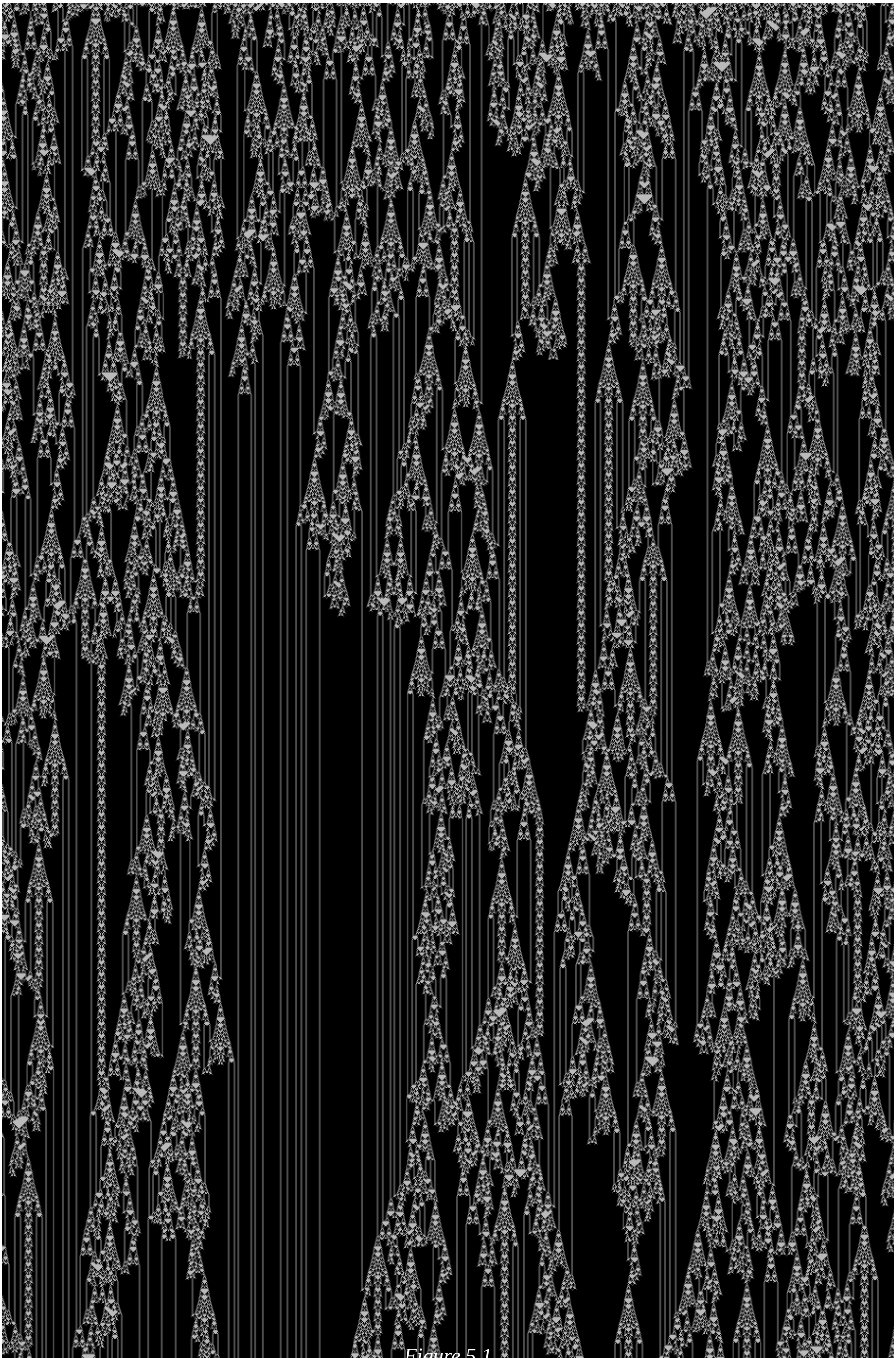


Figure 5.1

The structure, organisation and complexity of Elementary Cellular Automata by Stephen Wolfram.

In 1953, Russian mathematician Andrei N. Kolmogorov argued against the Turing Machine's limitation in dealing only with discrete computations and proposed a new model, together with his student Vladimir Uspensky, that allowed the equivalent of Turing's tape to be reconfigurable and therefore without the topological boundaries inherent in the Turing Machine (ibid:10). This affects the linearity of the computational process and thus the speed of its calculations. An extension of the *Kolmorogov-Usbensky Machine* is the *Schönhage Machine* (1970), which further extends the reach and dimensionality of the original concept of a tape proposed by Turing. In collaboration with Donald Knuth, the idea is described of a *Pointer Machine*, or *Schönhage-Knuth Machine*, that points to a register of natural numbers (ibid:12) as the basis for contemporary computational machines.

Neumann, The Universal Constructor and early Cellular Automata

In the 1940s, mathematician John von Neumann proposed and developed ideas of a self-replicating machine that could perform logical operations, through the use of a tape and a machine using a writing head or construction arm (Burks 1966). The similarity to the Turing Machine is obvious, but the intention was different in several ways. Firstly, it was founded upon an idea of self-replication, which is the ability to construct its own parts. Secondly, it sought to create successively more complex constellations from the axiom, initial state, comparable to the tendency in nature towards ever more complex organisations and thus systems that can perform ever more complex operations (McMullin 2000). The efforts of Neumann developed, among other things, the foundation for *Cellular Automata* (CA) based on the notion that a cell, in its simplest form, has one state. Neumann described a self-reproducing 29-state, 2-dimensional CA that could perform complex organisations and exhibit alterations or evolution over time (ibid).

The universal constructor as a concept and model for complexity has, in its constellation, aspects that awake scepticism. The first problem is that the initial axiom itself must have a constructor and, secondly, that growth and complexity in nature are based upon cell division and other operators, in contrast to the universal constructor envisioned by Neumann. The conceptual idea and its metaphysical principles of organisations nevertheless hold the basis for the organisation of increasing complexity. This approach remains essential and is still in need of further studies today in order to harvest its full potential (ibid).

Wolfram, A New Kind of Science

Such studies have been extensively performed by mathematician Stephen Wolfram, who, in the last three decades, has developed a series of rule sets based upon CA logics. The rule sets are simple cell states of 'black' and 'white', 'on' and 'off' or '1' and '0', depending on the setup and the operation of progressively adding them, according to previous cell states. The successive addition of cells that are the result of previous cell

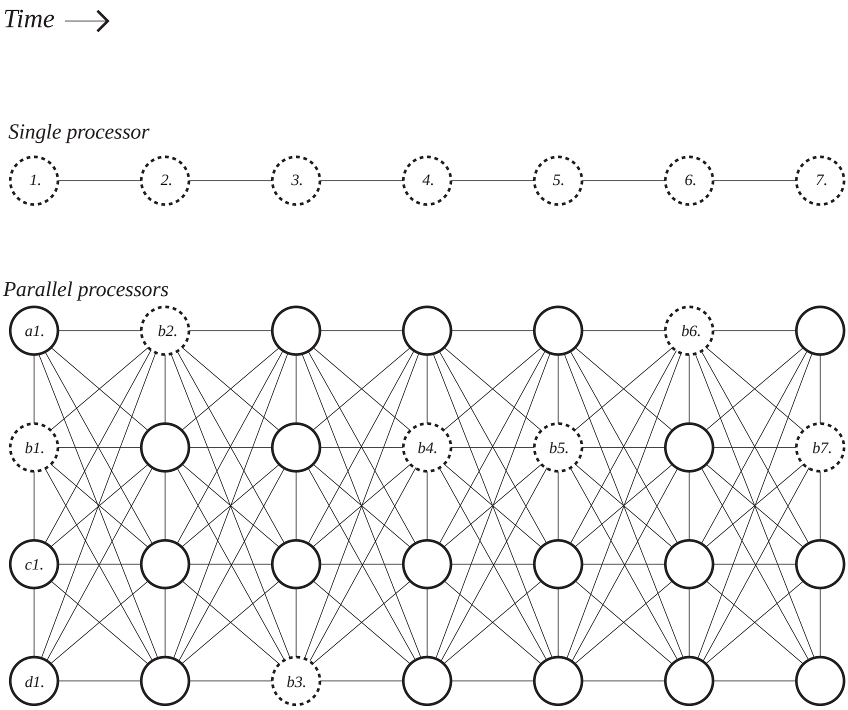


Figure 5.2

Scheme of singular and parrallel computing processes, illustrating the growing power and complexity of exchange between computing processing units with only a few parallel processes. Diagram by Isak Worre Foged.

states in the checkerboard spatial arrangement constructs infinite complex formations (Wolfram 1982)[Fig. 5.1]. The rule sets developed so far illustrate what Wolfram describes as universality (Wolfram 1984), and they illustrate this by solving complex phenomena in nature, such as chaotic patterns, fluid movements and growth processes.

Wolfram suggests from these studies that there is a move from analytical mathematics to computation for solving complex problems and proposes that this is a significant shift on the same scale as the shift from Newtonian physics to Einstein's relativity (Rocker 2006). In his subsequent work, Wolfram argued that the simple and local interacting organisations are capable of computing answers and thus confronts Hilbert's problem as stated above. Wolfram asserts:

> *More specifically, the principle of computational equivalence says that systems found in the natural world can perform computations up to a maximal ('universal') level of computational power, and that most systems do in fact attain this maximal level of computational power. Consequently, most systems are computationally equivalent. For example, the workings of the human brain or the evolution of weather systems can, in principle, compute the same things as a computer. Computation is therefore simply a question of translating inputs and outputs from one system to another. (Wolfram, 2002:5)*

Parallel and Distributed Computation

In the attempt to improve computational speed and task management, one branch of current research in computational science investigates parallel algorithmic techniques that can be described as *'sequential-time algorithms that can exhibit unbounded parallelism but only bounded sequentiality within a single step'* (Blass & Gurevich, 2003:22).

This approach allows computing tasks to be allocated on more than one processing unit (UTM/CPU) and therefore, theoretically, multiplies the power or inversely divides the processing cost of each unit [Fig. 5.2]. Previous research, however, illustrates a saturation effect of the computing capacities with the addition of computing units, saturation caused by interprocessing communication (IPC) that, after the coupling of just a few units, will need to allocate computing power to the communication between units, rather than to the actual task (Chu, Holloway, Lan, & Efe, 1980:57). Aspects of synchronisation, coordination, delay and interconnectivity become important issues in the successful application of a parallel or distributed computing system setup (Asanovic et al. 2006).

Research by computer scientists Wesley W. Chu et al (Chu et al. 1980) and Krste Asanovic et al (Asanovic et al. 2006) indicates several areas of potential in computational science for parallel and distributed methods in relation to the optimisation of processing costs of, for instance, energy and financial economics. Current models are *Multicore Models*, *Cluster Models*, *Grid Models* and *Cloud Models*, the latter being based on Grid Models, but expanded based on the Internet as an infrastructural communication system (ibid).

Distributed systems allow for 'global performance based in local actions (or local agency), task allocation, system redundancy and collective intelligence'. The systems perform generally as ecologies where the behaviour of the system is vastly complex with unpredictable consequences given the large quantity of unknown factors and their constantly changing relationships. An example can be seen in the altering connectivity from cluster/sector-based systems (strong regional connections and few global connections) in the financial environment to an intensified connectivity to a global system. This computational system process was part of the lead-up to the vast global effects of the 2008 financial crisis (Harmon et al. 2010). At a certain complexity level, a system, be it financial or cultural, will collapse due to the intensified relations (Weinstock 2010) and thus entirely lose its ability to maintain system redundancy and functional performance.

Natural Computing

Sequential programming remains a favourable model in most computational frameworks due its lower handling complexity compared to parallel or distributed systems in computing based on silicon processors. A turn towards several processing cores and thus extensive parallelism is, however, predicted as the immediate path forward in regards to improvements of machine processing performance in relation to costs of computing (Asanovic et al. 2006).

While the aforementioned Cellular Automata can execute on a sequential computing device (single CPU machine), as explained below, it illustrates a system of multiple local behaviour and thus multiple local actions and multiple local computations. This form of distributed actions exhibits capacities in solving global problems of a system but with lowered cost if following the argument of extended performance with reduced cost based on parallelism.

Furthermore, rather than extensive analytical, mathematical constructs, form is able to evolve based upon explicit and local descriptions between acting agents. If these relationships are informed by intentions related to construction, material and environmental aspects, a general integral system might be devised that would be instrumental for an Environmental Tectonics approach.

A branch of computational science, *Natural Computing*, applies the use of active agency to computation. And, as is outlined further below, natural computing covers a field that is of particular applicability to the formulation and instrumentation of Environmental Tectonics as related to the preceding propositions and research questions. As a computational field, it is divided into three classes and methods: (1) those that take inspiration from nature for the development of novel problem-solving techniques; (2) those that are based on the use of computers to synthesise natural phenomena; and (3) those that employ natural materials to compute (Castro 2007). Castro provides a definition:

> *Natural computing can be defined as the field of research that, based on or inspired by nature, allows the development of new computational tools (in*

software, hardware or 'wetware') for problem solving, leads to the synthesis of natural patterns, behaviors, and organisms, and may result in the design of novel computing systems that use natural media to compute. (ibid:3)

The first class covers the logic applied to a given problem through problem-solving processes in nature and attempts through this approach to solve problems in different scientific fields. The second class suggests the use of machine computation to perform a set of operations to explore or reveal natural phenomena, in particular the generation of natural patterns, forms and behaviours. Below, three such methods are described as instrumental techniques under the section Machine Computation. The third class suggests that organic, non-silicon-based materials can compute solutions. Core methods for computation, by organic material processes, are predominantly conducted within the field of biochemistry on a molecular scale (ibid). However, as has been discussed in the previous chapters, such methods are not foreign to architectural processes and architectural design intent. The use of matter to perform computation as logical processes is examined in the section Material Computation.

5.2 Machine Computation

A large, and constantly evolving, group of nature-inspired computational methods related to complex organisations exists (Brownlee 2011). By building on the propositions from previous chapters, a computational method should illustrate an iterative and integrative process. This, it is argued, enables the designer to understand the formation process and from this gain a potentially deeper understanding of the problem statement and solution statement. This again implies a progressive and selectionist process in which a candidate (design proposal) is measured against an assessment criteria, such as an intended perceived temperature, again and again improving upon experience. Such progressive methods are in fact similar to expert design processes that move towards novel design decisions, by rapid trial-error progression (Akin & Lin 1995) supporting the claim of the prior seminal works provided by architect and design process researcher Christopher Alexander (Alexander 1964; Steadman 2008) but extended through computational non-linear processing enabled by the systems and models described above.

The intent is to extend an instrumentality from 'computerisation', where output is a direct product of input, as is the case when drafting drawings on a computer aided design (CAD) drawing programme, to 'computation', where the output is substantially advanced from the input by the designer (Terzidis 2006). From Jason Brownlee we obtain a taxonomy on artificial intelligence algorithms that is based on nature-inspired programming, as *'Artificial Intelligence is therefore concerned with investigating mechanisms that underlie intelligence and behavior'* (Brownlee 2011:4).

The framework of mechanisms that present an 'intelligent' behaviour can be described as having metaheuristic properties (ibid.), which have been outlined by Blum and Roli (Blum & Roli 2003). They stated that:

- Metaheuristics are strategies that guide the search process.

- The goal is to efficiently explore the search space in order to find near-optimal solutions.

- Techniques, which constitute metaheuristic algorithms, range from simple local search procedures to complex learning processes.

- Metaheuristic algorithms are approximate and usually non-deterministic. They may incorporate mechanisms to avoid getting trapped in confined areas of the search space.

- The basic concepts of metaheuristics permit an abstract-level description.

- Metaheuristics are not problem-specific.

- Metaheuristics may make use of domain-specific knowledge in the form of heuristics that are controlled by the upper-level strategy.

- Today's more advanced metaheuristics use search experience (embodied in some form of memory) to guide the search.

In funnelling the large set of computational methods towards addressing the research questions posed, two machine-computational systems are further described, which poses the above characteristics in full or in part, these being *Fractal Systems* and *Evolutionary Systems*. Both systems are based on the inherent characteristics of parallel processing, environmental integration and developmental properties.

Fractal Systems

Fractal systems are based on the mathematical descriptions of self-similarity. '*In general, fractals are characterized by infinite details, infinite length, self- similarity, fractal dimensions, and the absence of smoothness or derivative*' (Castro 2007:16). The complexity of the fractal structure is measured by its dimensions, which is determined by its self-similarity dimension, defined as (Castro 2007:17):

$$N = (1/m)^d \implies d = \frac{\log N}{\log 1/m} \qquad (5.1)$$

With *m* being the scaling factor and *N* being the number of copies. The intriguing aspect of fractal geometry in mathematics and computer science is perhaps more obvious than the aspect found in architecture. However, in relation to this thesis, the power of fractal geometry, fractal dimensions and fractal behaviour can be seen in its property of a very simple starting condition. From this offset and through a simple set of logical instructions, advanced compositions develop. The capacities of such systems, as claimed by fields from biology to economics, infrastructure planning and psychology, is exhibited by the inducing and regulating behavioural processes (Castro 2007; Kari & Rozenberg 2008; Peak et al. 2004). The simplicity of the elements, its organisational system and potential formations, points back to the Element, System, Formation instrumentality identified and elaborated in the previous chapter. Two specific methods of fractal properties related to the above instrumentality are the Lindenmayer Systems and the prior discussed Cellular Automata System.

Lindenmayer Systems

The construction and examination of empirical and theoretical biological systems as Lindenmayer Systems (L-Systems) were first developed by biologist Aristid Lindenmayer in 1968, as a theoretical framework for studying the development of simple multicellular organisms (Prusinkiewicz & Lindenmayer 1990:vi). Since the initial underlying framework of L-Systems was conceptualised based on a rewriting procedure in which the elements of the system are called again and again, it has developed into different branches of inquiry. The strands span from 'deterministic context-free' systems (DOL-Systems) to 'stochastic context-sensitive growth modelling' systems (Knutzen & Saito 2009; Měch & Prusinkiewicz 1996; Jirasek et al. 2000), allowing a very diverse application of the, in principle, simple procedural method.

Ruleset	*Output*
$\omega : a_r$	1: a_r
$p_1: a_r \rightarrow a_1 b_r$	2: $a_l b_r$
$p_2: a_1 \rightarrow b_1 a_r$	3: $b_l a_r a_r$
$p_3: b_r \rightarrow a_r$	4: $a_l a_l b_r a_l b_r$
$p_4: b_1 \rightarrow a_1$	5: $b_l a_r b_l a_r a_r b_l a_r a_r$
	6: $\ldots$

The DOL system contains an axiom and a set of elements, listed as above, a and b, et cetera, and a rule to distribute the elements in forward iteration. By simply rewriting each iteration progressively based on the previous one, the underlying organisational complexity of organic structures can be obtained [Fig. 5.3]. Variation arrives from varying elements and the rule that redistributes the elements in a future iteration. By extending this method with graphical elements to the underlying mechanism, known

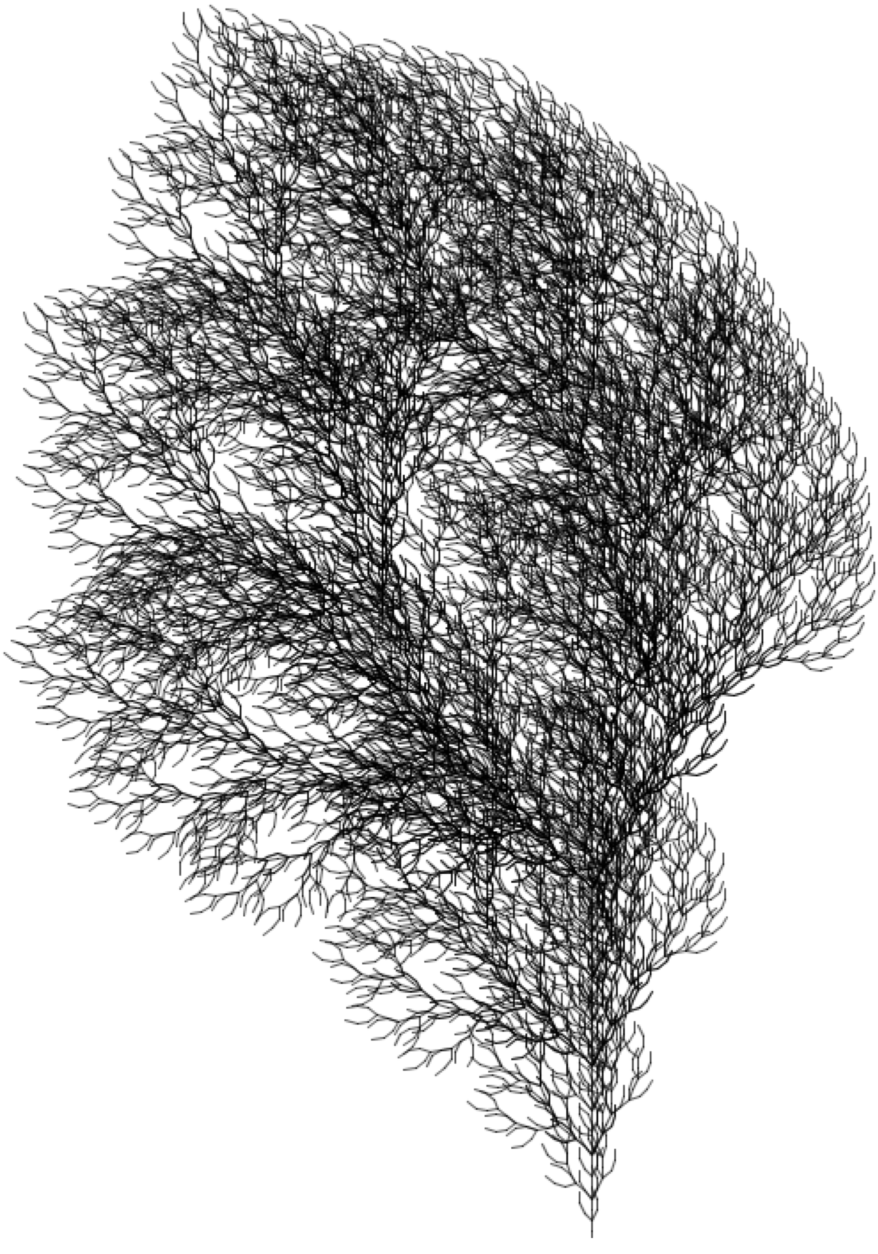


Figure 5.3

Generation of context-based structure by L-Systems following the algorithmic structure on page 199. Drawing and code by Isak Worre Foged based on Daniel Shiffman's book 'The Nature of Code'.

as turtle interpretations, a visual structure is revealed and the progressive appearance of growth processes is accessible. The turtle interpretation of rewriting systems is commonly based on its elements and its rules as laid out below (Prusinkiewicz & Lindenmayer 1990):

Ruleset

$$n = 5$$
$$\delta = 30$$
$$\omega : F\ -\ +$$
$$p : F \rightarrow FF + [+F - F - F] - [-F + F + F]$$

With n = iterations, δ = rotation angle, ω = elements, *p* = rule. [Fig. 5.3]

The application of this method is advanced by additional techniques to influence the growth-modelling procedure illustrating the extensibility of the organisational logic, but with the same underlying mechanism as shown above. It is, however, not solely a question of form, but also of information and energy structures. The form of fractal branching exhibited in L-System organisations is inherently related to distributional laws in nature, defined by Murray's Law. Sherman asserted:

> *A large part of the branching vasculature of the mammalian circulatory and respiratory systems obeys Murray's law, which states that the cube of the radius of a parent vessel equals the sum of the cubes of the radii of the daughters. Where this law is obeyed, a functional relationship exists between vessel radius and volumetric flow, average linear velocity of flow, velocity profile, vessel-wall shear stress, Reynolds number, and pressure gradient in individual vessels. In homogeneous, full-flow sets of vessels, a relation is also established between vessel radius and the conductance, resistance, and cross-sectional area of a full-flow set. (Sherman 1981)*

Form, as based on fractal structures, exhibit in turn instrumental capacities in its ability to immerse itself in an environment by extending its environmental connections (covering an area or volume) and at the same time organise its internal connectivity of energy and information properties.

While no records of Utzon's many projects exhibiting branching have been shown, it is reasonable to note that the inspiration for much of his architecture is related to additive processes of self-similar elements. Furthermore, the organisational system, as can be seen in projects from Expansiva, Kingo Houses and in particular the unbuilt (second project) Asger Jorn Silkeborg Museum [Fig. 5.4], has clear traits of a recursive rewriting of elements unfolding in a landscape of organisational and environmental forces.

The originators of the L-Systems methodology, Lindenmayer and Prusinkiewitz, point to the English theoretical biologist Darcy W. Thompson for an assertion on such mechanisms:

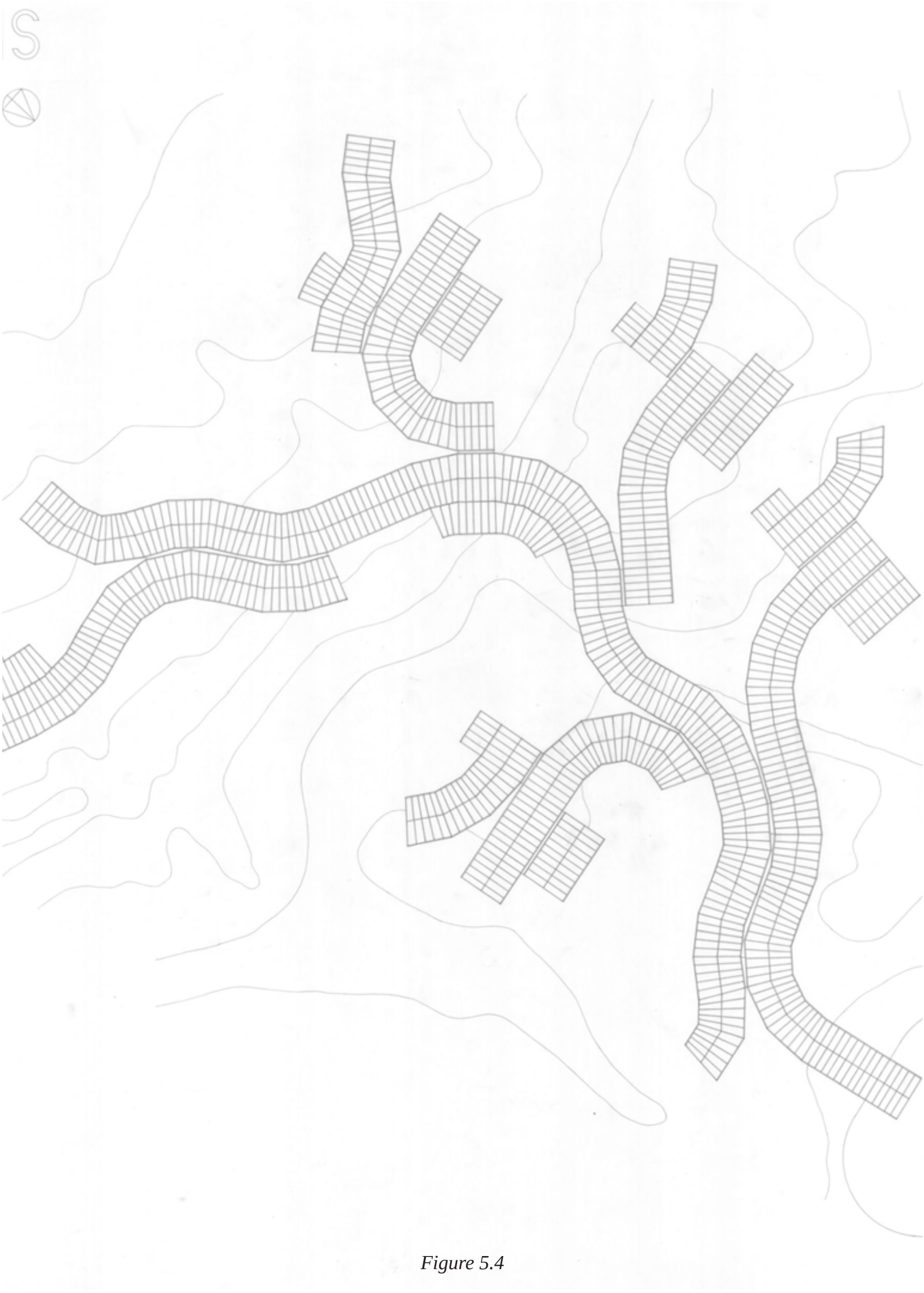


Figure 5.4

Silkeborg Museum (1970) showing the branching and fractal like structure of Utzon's design. .Drawing by Jørn Utzon.

> *Organic form itself is found, mathematically speaking, to be a function of time.... We might call the form of an organism an event in space-time, and not merely a configuration in space*. (Thompson 1992)

This notion of growth modelling is, in its wording, closely related to the prior descriptions of architectural constructs, as stated by architectural theorist Sanford Kwinter, architectural scholar Michael Hensel and the proposition on environmental constructions as suggested in earlier chapters. The developmental model of form and structure is explicitly connected to time, which illustrates how an instrumental model can support temporal conditions as an architectural design method.

Cellular Automata Systems

Lindenmayer and Prusinkiewitz pointed back to an earlier developed procedure for examining and exploring generative growth modelling, or, more precisely, the intent to construct evolutionary modelling (Prusinkiewicz & Lindenmayer 1990:62), namely Cellular Automata. Already listed above as a general form of computation, CA was developed as an abstract model for evolutionary processes by mathematicians Stanislaw Ulam and John von Neumann (McMullin 2000; Beyer et al. 1985). CA makes use of progressive mechanisms of iterative rewriting similar to L-Systems, but through very different logical and graphical procedures [Fig. 5.5]. In particular, von Neumann was, as mentioned earlier, focused on the ability to construct a system that enabled reproductive capacities identical to biological systems (McMullin 2000).

While CA has been explored in several fields, due to its versatile properties, aforementioned mathematician Stephen Wolfram has systematically explored the mechanisms and underlying systems theory. Wolfram is particularly interested in the simplest form of CA, 'elementary' CA, as he argues it posits the greatest universal computational powers. Wolfram posits:

> *An 'elementary' cellular automaton consists of a sequence of sites carrying values 0 or 1 arranged on a line. The value at each site evolves deterministically with time according to a set of definite rules involving the values of its nearest neighbours. In general. the sites of a cellular automaton may be arranged on any regular lattice, and each site may take on any discrete set of values*. (Wolfram 1982:2)

Similar to the L-Systems, CA is based on simple elements, organised in a system of rules that allows formations of geometric structure to immaterial behaviour. Furthermore, both methods may integrate the description of an environment to which formations can be influenced. While both methods are based on discrete entities as singular elements organised in a system, they can be observed to exhibit the unified interrelations between what structure is and what is considered environment, as discussed in previous chapters. While L-Systems can be formally described as context-free, it is difficult to imagine a CA where context is omitted, as a cell state responds directly to its neighbour (environment) for every iteration computed.

This is particularly evident in the CA method of *Game of Life*, invented by John Conway (Gardner 1970). Here, the CA is organised in a two-dimensional or three-dimensional system,

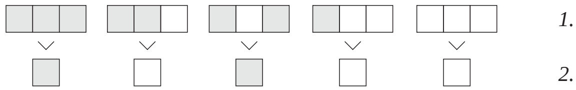


Figure 5.5

The basis for elementery CA is the reading of elements in one line (1. iteration) to produce the resulting line (2. iteration). A rule set is defined by a set of instructions, where the organisation of three elements determine the immediate cell property below, as can be seen above. From the combined rule set arise formations, as can be seen in figure 5.1. Diagram by Isak Worre Foged.

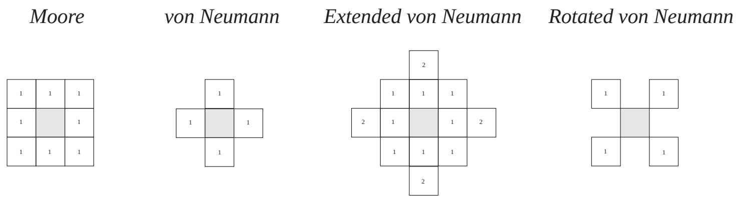


Figure 5.6

The basis for Game of Life CA is the definition of neighbourhoods combined with a rule set similar to figure 5.5, but described in 2 or 3 dimensions. A Moore neighbourhood represents the uniform 'standard' organisation, while a Rotated von Neumann represents a different method for including element neighbour information. The definition of the neighbourhood influences the local interaction and the global behaviour of the system. Diagram by Isak Worre Foged.

rewriting the entire system surface or volume simultaneously, rather than line by line, as is the case in elementary CA. The neighbourhood [Fig. 5.6], or environment, of each element determines the element's state in the following iteration. Complex formations can be observed, dependent on element state description, element rule description and element neighbourhood description [Fig. 5.7].

Any of the three aspects may have a significant impact on the development procedure and thus the ability of the system to uncover solutions and problems. The notion of environmental boundary, an inner and outer environment, as formulated by Herbert Simon, is clearly visible by using different CA neighbourhood constellations. Specifically, when the neighbourhood rule is changed (the boundary to which each cell 'observes' for its next iteration), the configuration of what is inner, for instance state 0, and what is outer, state 1, is determined.

Both elementary and Game of Life methods of CA have been identified as instrumental methods for modelling complex natural geometric visual patterns (Wolfram 2006), complex biological microstructures and their functional behaviour (Basanta et al. 2003; Peak et al. 2004) in planning and urban development (Santé et al. 2010; Batty 1997).

While fractal geometry, based on machine computational processes, is commonly identified and classified by its visual characteristics, it is evidently dependent on environmental description and interaction to unfold.

Environmental integration is explicitly present in developing the systems from one iteration to the next, as is shown above. This is different from how the natural computing methodology of evolutionary algorithms functions. Environment and its integration in such systems are assessed between iterations (generations) as a means to evaluate the system. This form of separation is also present in other aspects, foremost among them the biological distinction of 'genotype' and 'phenotype' depicting the system of logical procedures and the system of physical embodiment.

Evolutionary Systems

Computer scientist David B. Fogel et al (Fogel 1997; Fogel 2000; Bäck & Fogel 2000a) promotes the application of evolutionary algorithms based on a series of characteristics, which may enable the previous propositions and the initial theoretical and instrumental objectives in this thesis. Evolutionary machine-based computational systems can be described as having the properties laid out below:

- A determined goal does not need to be described, only whether a proposed solution is better than another. This enables the simple description of better or worse even when facing complex interrelated problems.

- Adaptability to the problem statement, meaning that the algorithm is open to a problem arising or changing during the search for a solution. This makes the algorithm robust in relation to changes during a design process.

Figure 5.7

Game of Life generated by a three-state CA model with multiple rule sets. The dynamic behaviour of the model can be modelled towards exemplifying complex phenomena such as forst fire's and airflow patterns in plant leaves. Drawing by Isak Worre Foged based on code by Daniel Shiffman.

- Implicit parallelism is at the core of the algorithmic mechanism, using populations, local evaluation, to precede a global solution. This also indicates that distributed computation can be performed on both a sequential and a parallel setup, enabling expansion of the computing power.

- The quick generation of 'good enough' results to be of use in a solution- and problem-finding process. This enables the algorithmic approach to be used in conceptual and initiative design procedures, rather than only as a post-optimisation technique.

- The evolutionary algorithm has the ability to learn from its own actions, moving beyond the potential lack of knowledge of the human designer to search for or identify new solutions or problems.

Evolutionary systems based on Genetic Algorithms were initially formulated by John Holland during the 1960s and 1970s, as *'computer programs that "evolve" in ways that resemble natural selection can solve complex problems even their creators do not fully understand'* (Holland 1992). Since then, they have, through the last decades, evolved themselves through the work of, among others, Holland and David Goldberg (Goldberg 1988; Goldberg 1989; Goldberg 2002), Melanie Mitchell (Mitchell 1995; Mitchell 1998), Bäck and Fogel (Bäck & Fogel 2000a; Bäck & Fogel 2000b) in how they are organised to various sub-optimised procedures by altering the fundamental constituents of:

- Problem statements (definition of a search space)

- Reproduction mechanisms (selection, crossover, mutations, replacement)

- Solution statement (definition of a fitness description)

The fundamental techniques of evolutionary computation follow the theory of natural selection as discovered and described by Charles Darwin in his seminal publication *On the Origin of Species* (Darwin 1859). Just as the original Darwinian theory has undergone several alterations and additions, so has the evolutionary computation evolved. The basis for the algorithmic mechanisms in its conceptual construct, however, nevertheless follows the same basic procedure [Fig. 5.8]:

(1) Initialise a population.
The construction of a population can vary from a few individuals, such as 50, to thousands, such 10000 or more. The smaller the population size, the less coverage of the solution space and vice versa. This indicates that a higher population size is always preferable; however, this may dramatically slow the processing speed and thus the ability to reach a solution in a reasonable time (Shiffman et al. 2012), effectively reducing the capacity of the technique in a negative direction.

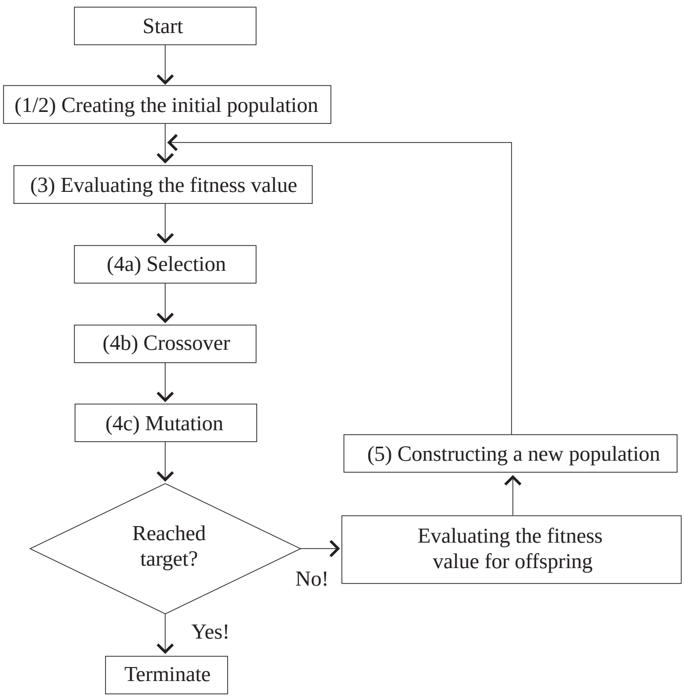


Figure 5.8

Standard scheme of the genetic algorithm procedure, which loops based on the search for solutions that match as the criteria's descriped through the fitness function. Diagram by Isak Worre Foged.

(2) Vary the individuals of the population by a random or specified factor.
In varying the individuals of the population, the search space is covered. If a search space is enormous, that is, the amount of combinations in relation to population and combinatorial techniques, specified search modes can be used (Fogel 1997) and thus tailor the search according to the problem of interest.

(3) Evaluate the fitness of each individual in the population
An evaluation of each individual requires, logically, something to compare the individual to. This implies a cost function, also known as a performance criterion or fitness function. Often, a number or function in a simple or concatenated form represents this for objective selection. The designer could equally be implicated as a subjective part of the selection process (Sastry et al. 1975). However, in case of a search with an unknown solution, other search modes can be used, such as minimisation or maximisation. When individuals are evaluated for fitness, they are commonly ranked for reproduction processes.

(4) Reproduction by operator selection, crossover, mutation and replacement.

a. Selection
Selection allocates the better candidates (individuals) of the population in a group. This can be done by simply taking the top level or best fitted candidates, or through various techniques showing a better overall performance than if only, for instance, the top ten percent are chosen. Such techniques include ‘roulette-wheel’ selection [Fig. 5.9], ‘stochastic universal’ selection, ‘ranking selection’ and ‘tournament’ selections (Sastry et al. 2005).

b. Crossover
Crossover combines the genes from two (or more) individuals into an offspring with a different (and hopefully better) set of genes in relation to the fitness function. A simple combinational technique is to take half from each parent, a ‘one-point’ crossover (1), though many other sophisticated techniques have been developed with significant performance improvements, such as ‘two- point’ crossover (2), ‘uniform’ crossover, ‘order-based’ crossover, ‘partially matched’ crossover and ‘cycle’ crossover (ibid.) [Fig. 5.10].

b. Mutation
Mutation is inserted to avoid the candidate solution search getting stuck on a wrong solution path, known as local maxima and local minima. Mutations are performed on the genes involving one or more changes to the combination provided by the crossover procedure. The mutation rate is often low, which means that, for instance, 1 in 1000 is altered. If the mutation rate is very high, the progressive process of improvement is destroyed, while a very low mutation rate will not allow random regions of the search space to be sufficiently investigated (Bäck & Fogel 2000a; Shiffman et al. 2012).

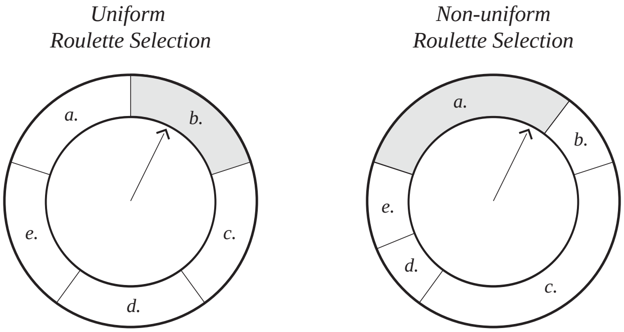


Figure 5.9

Diagram of a Roulette Wheel selection method illustrating a uniform, equal oppotunity for selection and a non-uniform probabilistic opportunity for selection. By this procedure the evolutionary process can be steered to favour some solutions (proposals) over others. Diagram by Isak Worre Foged.

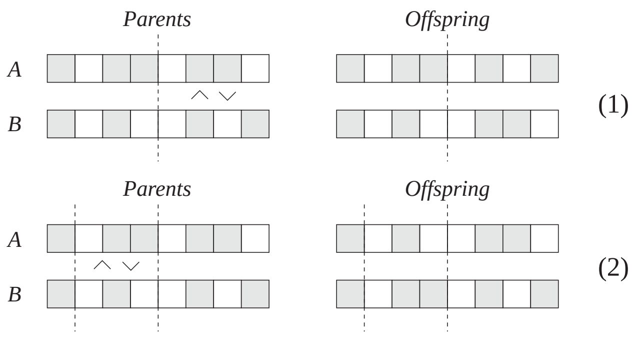


Figure 5.10

The crossover procedure enabling the development from parent to offspring by single (1) and double (2) cutting techniques. The positioning of the cutting location in both techniques evidently modifies the conditions for describing the offspring genotype. Diagram by Isak Worre Foged.

(5) Replacement
Replacement is done by the created offspring replacing the original (previous generation) parental population. This, again, can be done through several techniques, such as 'elitist' replacement, 'generation-wise' replacement and 'steady-state' replacement (Sastry et al. 2005).

The first introduction for a machine computation approach to architecture was envisioned by John Frazer in his work with *An Evolutionary Architecture* (Frazer 1995): Frazer illustrated both conceptual and applied examples of evolutionary procedures as initiative elements of the creative design process's classical problems, such as spatial organisation of a gymnasium (ibid:22). Frazer also showed more abstract notions of adaptation through self-organising interactive environments such as the Universal Constructor (not to be confused with the universal constructor by Neumann) (ibid: 49). Beyond the internal evolutionary processes directing the generation of form, Frazer introduced environmental external cost functions in the process of form generation in the development of a yacht hull together with Peter Graham. Despite being two decades back, the work of John Frazer with Julia Frazer and with assistants and students is still relevant and as state-of-the-art as conceptual contemporary architectural models.

Within the thesis introduction chapter, the contemporary state-of-art in evolutionary computation combined with environmental assessment has already been discussed. Methods applied tend to focus on relatively simple single-objective and multi-objective methods. Accelerating focus and volume of work in computer science explores the underlying mechanisms of evolutionary algorithms, as shown by David Goldberg, Melanie Mitchell and others. These studies examine combinatorial methods for gene reproduction to methods of population grouping. In turn, other efforts may be more relevant to an architectural inquiry of evolutionary models. In fact, it has been shown that the current application of miscellaneous optimum-seeking algorithms, through evolutionary processes, has a generally limited precedence from specific algorithmic methods to methods in terms of its properties in searching a potential solution field. Computer scientists Wolpert and Macready stated:

> *We show that all algorithms that search for an extremum of a cost function perform exactly the same, when averaged over all possible cost functions. In particular, if algorithm A outperforms algorithm B on some cost functions, then loosely speaking there must exist exactly as many other functions where B outperforms A. Starting from this we analyze a number of the other a priori characteristics of the search problem, like its geometry and its information-theoretic aspects. This analysis allows us to derive mathematical benchmarks for assessing a particular search algorithm's performance. We also investigate minimax aspects of the search problem, the validity of using characteristics of a partial search over a cost function to predict future behavior of the search algorithm on that cost function, and time-varying cost functions.*
> *(Wolpert & Macready 1995)*

Hence, the general application of evolutionary processes by machine computation might best be applied in supervised architectural design processes. This promotes an approach in which a general method explores and searches design parameters and solutions, rather than the investigation of the algorithmic sub-mechanisms, which is the core agenda in computer science. While the architectural agenda may be oriented towards an application, it nevertheless requires an understanding of the evolutionary mechanisms in order to apply the method successfully against a given design problem (Deb 2009). And, as researcher in architectural design processes, Bryan Lawson posited: *'Recognising the nature of the problem and responding with an appropriate design process seems to be one of the most important skills in design'* (Lawson 2006:108).

As stated by Lawson and others (Lawson 2006), an architectural problem is normally ill-defined and potentially unknown. This realisation aligns well with the definition of meta-heuristic algorithmic characteristics in that various and loosely defined design problems can be addressed by such algorithm procedures. Conversely, while it may be ill defined, the formulation of what to search for becomes an intrinsic task in itself. The formulation of an architectural fitness function, which serves to explore and inform the design and the designer, thus requires the assessment of architectural intentions, which in the context of this thesis could be the formulation of an atmosphere by environmental construction.

It can be suggested that the definitions of the problem statement and fitness statement become the central aspects to be explored in the application of evolutionary machine-based processes in architecture. This highlights two immediate consequences. Firstly, the formulation of the problem statement (definition of the search space) is understood or initially explored towards a definition that can be embedded into the algorithm. In a matter-based practice, as proposed in the previous chapters, that means understanding and defining the physical and metaphysical conditions of the design problem and converting these into machine-computational descriptions. Secondly, the fitness statement (definition of what to search for in the search space) is either understood or open to exploration during design progression. This is necessary to accommodate what British architectural theorist Philip Steadman points out as the most important difference between biological evolution and the evolution of design, namely the active influence of a designer (Steadman 2008).

This is not only a consequence of the designer's active participation in the evolutionary process. It may also be seen as an advantage over organic evolutionary processes in the search for solutions through the combination of progressive iteration by the algorithm and cross-connections of ideas. This is made possible by the understandings developed during the evolutionary process. Steadman asserted:

> *One significant contrast between technological and organic evolution, recognized by the cultural evolutionists, was that which was signalled by the difference in the shape between the 'family tree' of organic species and the 'family tree' of artefacts. From the definition of organic species, it followed that once having diverged to the point of splitting into two or more distinct species, these separate branches could never in the future join up again to*

> *reform the original species nor could they ever merge with others*. *(Steadman 2008:97)*

This supports the argument that the capacity of the evolutionary process in design is not only the ability to find solutions but, in an equal manner, to uncover problems and ways to combine design trajectories to explore a design condition and design phenomenon. This, again, points to the statements above on the performance of search algorithms by Wolpert's theorems (Wolpert 1996). This is the case, as guided or supervised machine learning algorithms do not show significant numerical performance differences. Scientists Walter Fontana and Leo Buss assert in their work on dynamical systems and bounded organisations that:

> *It bears emphasis that 'objects', as we frame them here, are defined by structure- action relationships where each action is a mapping from structures to structures. In a many-body setting this generates a constructive feed-back loop (in analogy to dynamical feed-backs) which causes the emergence of 'organization'. The so-defined constructive feed-back is absent in genetic algorithms, genetic programming, classifier systems, and models of evolutionary optimization. While these systems deal with objects whose structure entails action, the action does not participate in object construction. This is exactly what puts our concept of organization outside their scope. (Fontana & Buss, 1996:48)*

And:

> *...Second, it is often desirable to leave uninterpreted the nature of the objects when one is seeking to implement a system whose objective is a search. Holland's genetic algorithms and classifier systems need not be faithful chromosomes or genotype-to-phenotype representations when the intended objective is an efficient search engine*. *(Fontana & Buss, 1996:48)*

What seems to be of importance, then, is the ability of the designer to formulate, explore and re-formulate the conditions for the evolutionary search procedure, factually evolving the evolutionary setup in parallel. This form of architectural design activity thus points not only to the production of architectural artefacts, but to the making of design processes that intentionally search for phenomena creation as advocated by philosopher of science Ian Hacking and the search for revealing by appearance, as stated by Martin Heidegger.

By the conceptual and physical separation of the machine-computational structure, as devised by Alan Turing et al, computational processes today remain separated from the physical construct, the hardware, supporting the computational processes. In the evolving field of natural computation, a material's ability to compute is increasingly investigated, as was already implied in the Introduction chapter with the example of an adaptive system.

5.3 Material Computation

As has been stated above by Fontana and Buss, by analysing organisational structures, machine-based evolutionary processes lack the fundamental making of the initial element. This process, in contrast, is present in organic processes by moving 'down' through the scales of construction. Thus, material computation as an evolutionary procedure exhibits extended properties in this respect. As noted above, this problem in terms of constructing a true evolutionary model was also part of the critique von Neumann faced in his work with formulating reproductive machine-based cellular automata models (McMullin 2000; Burks 1966). However, as the objective here is to identify, elaborate and apply instrumental methods and models for architectural Environmental Tectonics, the critique Neumann faced on true biological reproductive processes seems unrelated. Nevertheless, the application of organic material computation promises something beyond current machine-based computation. Scientist Nancy Forbes refers to IBM Research when identifying the problem of silicon machines and the inverse potential of organic machines, as she states:

> *When silicon microelectronics reaches ultimate physical limits to further miniaturization, the smallest silicon transistor will still contain over a million atoms. Yet, there is no fundamental reason why switches that process information cannot be made far smaller than that. (Forbes 2000:83)*

While computer scientists are concerned with the size of computational systems, these issues appear to be of less relevance in architecture. In comparison, robotic sciences, an interdisciplinary field between the physical design of robots and the construction of artificial intelligence to control the robot, has shown material computing methods that may be more closely related to architectural agendas.

Recently, researchers in robotic and material sciences have increasingly looked to material behaviour as a form of embedded computation (Spoonberg & Full 2007; Hoffmann & Pfeifer 2012; Spagna et al. 2007). These studies are conducted to understand the solution handling in animals with very little processing power and energy to use for it. The studies indicate that a large part of a responsive behaviour in an environment is embedded in the elasticity of muscles and the functions of tendons and skeletons to contract and expand without neural activity. Also, and with some contradiction, muscles seem to operate without contact with a central neural processor. From this, the studies show that some muscles accomplish neural processes. Thus, it allocates direct intelligent computational processes in a much more parallel and distributed manner than the conventionally perceived central processing paradigm. It concludes that a form of local responsive behaviour is functioning through a matter property without utilising a central unit for control signals. In an architectural context, Michael Hensel and Achim Menges assert:

> *Natural systems are now seen not so much as something from which to draw formal order for design as offering a guide to how one can design with the performative qualities of materials, entraining forces and material effects. (Hensel & Menges 2006:10)*

This orientation has resulted in early architectural studies with a turn towards the application of materials that have directional differences in structural properties, also known as 'anisotropic' properties (Hensel & Menges 2006b; Hensel 2010; Hensel 2012; A Menges & Reichert 2012; Reichert et al. 2013). These aforementioned efforts utilise the specificity inherent in the material makeup rather than suppressing these properties. This approach to material autonomy and internal constructs has been followed by several other researchers in architecture focusing on studies of different material properties and exploiting these in models that manifest behaviour that is responsive to their local environment (Achim Menges & Reichert 2012; Mossé et al. 2011; Pasold & Foged 2010; Ayres 2008).

This suggests that at least part of the computational structure and procedures is invoked by the organisation of matter (material-environment) and thus supports earlier propositions made regarding Environmental Tectonics. What is less clear is to what degree these material systems complete genuine adaptive properties, as seen in machine-learning systems, if they are purely linear responsive mechanisms. To clarify the distinction, Oxford English Dictionary defines *'responsive; reacting quickly and positively'*, while *'adaptive; make (something) suitable for a new use or purpose; modify'* (OED, 2011). To be adaptive, an extended property of responsiveness by modification is needed. In dissecting how an adaptive system is described in biology, Michael Hensel refers to the biologist Tibor Ganti.

> *According to Gánti, the former are necessary for an organism to be in a living state, while the The Principles of Life latter are necessary for the organism's survival in the living world. Real-life criteria are: 1) inherent unity – a system must be inherently an individual unit; 2) metabolism – a living system has to perform metabolism; 3) inherent stability – a living system must be inherently stable; 4) an information-carrying subsystem – a living system must have a subsystem carrying information that is useful for the whole system; 5) programme control – processes in living systems must be regulated and controlled. Potential life criteria are: 1) growth and reproduction; 2) the capability of hereditary change and evolution; 3) mortality. Synthetic-life research embraces a similar, if abbreviated, list of criteria, including containment (inherent unity), metabolism, heredity and evolution. (Hensel 2006a:20)*

If applied to architecture, this clarifies the terminology in terms of architectural classification of methods and models. Arguably, this positions the predominant current architectural research of material computation, listed here among others in the Introduction, within the group of responsive. It is effectively either visually dynamic or visually static, as quoted from the chapter by David Leatherbarrow, rather than adaptive. Further elaboration on this operational distinction is offered by Michelle Addington and Daniel Schodek, as they list their definition of smart materials with the following terms: 'Immediacy' (responding in real time), 'Transiency' (responding to more than one environmental state), 'Self-Actuation' (intelligence is internal to the material), 'Selectivity' (response is discrete and predictable) and 'Directness' (response

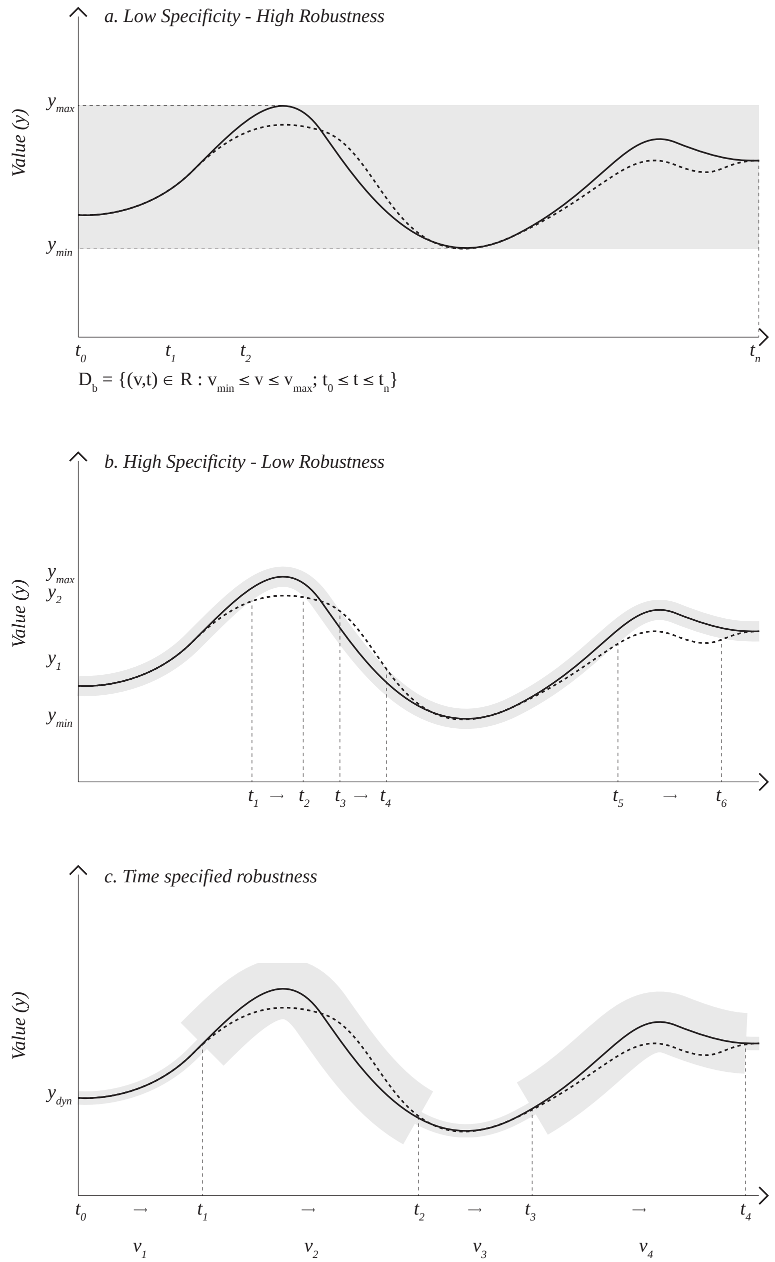


Figure 5.11

Diagram illustrating different strategies of response patterns to periodic changes. Top diagram illustrates the definition of a robust model including the entire span of modifications. The middle diagram shows the approximation of response to potential variations. The bottom applies the approximation strategy, but in specified time domains. Diagram by Isak Worre Foged.

is local to the activating event) (Addington & Schodek 2005:10). Their definition remains thus inside the above responsive domain, lending itself to predictable actions based on environmental changes.

This, however, affords a responsiveness to what we know in advance, not adaptation to unforeseen events. Systems modifying responses by machine motor-based actions are widely used today, such as the mechanically simple automatic window blinds based on sensor input and microprocessor decision-making (based potentially on machine-learning algorithms as described above). The attempt to construct adaptive, organic-based systems in architecture is nevertheless studied. Scientist Rachel Armstrong studies with this agenda, for example, the organic potential of moulds to inform growth patterns of cities (Armstrong & Ferracina 2013; Armstrong & Adamatzky 2013). With a similar approach, architectural scholar Alberto Estevez examines the potential to modify the genetic material of trees, so that leaves become light-emitting during dark hours, reducing the need for urban lighting (Estevez 2010). Both studies, however, are conducted in petri dishes in biological laboratories. The equivalent of organic material-based computation on an architectural scale remains currently responsive to predictable events. This is not, however, necessarily problematic in environmental conditions of minor changes, as responsive methods may be more adequate to act against these periodic modifications [Fig. 5.11]. Thus, at this point, it can be asked:

How is it possible to compute responsive behaviour towards dynamic foreseen and potential unforeseen environmental conditions?

Homeostatic Systems

Before approaching the above question more directly, it is relevant to outline the above material computational methods as responsive systems that attempt, in a simple manner, to balance the conditions between the outer state environment and the inner state environment. Furthermore, these responsive actions are executed across different scales, maintaining the proposition of a matter-based orientation. The regulatory mechanism, a responsive notion of material computation, is associated with the description of homeostatic systems. Such systems are defined by *'the tendency towards a relatively stable equilibrium between interdependent elements, especially as defined by physiological processes'* (OED, 2014) Effectively, it implies adaptive procedures through responsive feedback actions. For a responsive feedback system to perform homeostatic processes, a set of mechanisms must be imbedded into its material makeup, Michael U. Hensel asserts:

> *… Homeostatic systems require sensors to measure the parameters being regulated: signal transmission to a local or global control centre where the deviations from desired values are measured; control centres – if the measured values are different from the set points then signals are sent to effectors to bring the values back to the needed levels; and effectors capable of responding to a stimulus. (Hensel 2006a:24)*

In fact, homeostasis, being a biological term for adaptation to environment, forms the counter-argument to neo-Darwinian mechanisms as the basis for evolutionary and developmental processes. Adaptation by an organism's direct relation to its environment, rather than 'passively' through the selection of the fittest paradigm, as a predominant model for evolutionary development had been challenged even before the Darwinian theories were published and widely adopted. Biologist James S. Turner argues (Turner 2007; Turner 2012), based on the original ideas of biologist Jean-Baptiste Lamarck's concepts of evolution (Lamarck 1914) and the experiments conducted by physiologist Claude Bernard, for the adaptive capacities of homeostatic mechanisms as a principle for evolution. He asserts:

> *From his painstaking work came Bernard's signature idea, homeostasis: 'The constancy of the internal environment is the condition for a free and independent life.' Bernard stated it, if anything, too narrowly: homeostasis is a profound, and often misunderstood, assertion about the distinctive nature of life. Although Bernard himself was not an evolutionist, his concept has important evolutionary implications, for it holds within it the key to the core phenomenon of adaptation, and for restoring what the Darwin machine seeks to deprive: the purposeful striving of living systems to survive and prosper. In short, adaptation is the product, not of the soulless grinding of the Darwin machine, but of the hopeful striving of the Bernard machine. (Turner 2012:32)*

From this, homeostatic processes show the ongoing construction of an environment and an organic structure by feedback systems between a behavioural organism and its 'understanding' and interactions with an environment. This echoes the concepts of Uexküll that were presented earlier, which today are classified as the field of cybernetics and formulated as *'the science of communications and automatic control systems in both machines and living things'* (OED, 2014). Several theoretical adaptive models within this field and related to architecture have been presented (Ashby 1956; Ayres 2008; Cariani 2009), illustrating both abstract and technologically complex implementations of homeostatic systems constructed by humans.

Architectural studies exploring the literal integration of biological organisms as building parts can be found in the recent application of micro-organic substance as applied in the secondary façade for the BIQ House project by engineering firm ARUP (Wurm 2013). Here, the algae respond to exposure to sunlight and become bioreactors, thereby harvesting energy that can be used for electrical mechanisms in the building. Thus, the algae become an organic equivalent to the technological development of photovoltaics, both harvesting and converting solar energy. It can be discussed, however, to what degree the implementation of algae has a more profound influence on environmental articulation than that of conventional solar energy collectors.

Clearly, the adaptive capacity of cybernetic systems exceeds the singular responsive mechanism of smart materials as formulated by Addington and Schodek. This in turn suggests that material computation in architecture could benefit from a deeper integration of cybernetic-biochemical methods to fabricate materials of a higher response level to adaptive properties. The above examples from robotic science illustrate, however, that the application of responsive materials can also act as an effective method for non-technical built constructions influenced by environmental variations, with the latter being a central objective in this thesis. Hence, in moving towards an application of an Environmental Tectonics approach, it could be beneficial to search for responsive regulatory matter-based systems under a given domain of environmental variations to understand and programme material responses. Such an approach aims to address the duality of constructing specific environmental conditions and the construct of responsive robustness to general environmental fluctuations [Fig. 5.11].

In an extension of the above question, the question below can be formulated to pursue an instrumentality that allows evolutionary design models to integrate the dynamic properties of responsive behaviour.

How can these matter processes be embedded into evolutionary machine-based computational design models oriented towards an advanced form of instrumentality?

5.4 Hybrid Computation

Machine-based computation, as approached in this thesis, exhibits instrumentality by evolutionary models to Environmental Tectonics. This statement is discussed through the aforementioned adaptive systems arguments to neo-Darwinian mechanisms, via the application of, for instance, genetic algorithms. In material-based computation, focusing on embedded responsive mechanisms in relation to a given environment, Bernard mechanisms are argued to be of central importance to the notion of environmentally sustainable constructions.

As proposed earlier, Environmental Tectonics is not based on referentiality, or on autonomy. This suggests that from an architectural perspective, it is not contradictory to apply both evolutionary principles, even if at first they are in opposition when drawn from conventional evolutionary processes in biology. Rather, as an operational methodology, the hybrid use of both the Darwin and Bernard machines may unfold a new level of evolutionary instrumentality. And, as the objective of this work is not to formulate or construct exact biological or technological reproductive models, a modified design search, such as one conducted by human evolvement in the design processes, appears more promising to architectural processes, with the affordance of integrating human agency in making, as stated previously, towards revealing.

Reusing copper as an example may serve to illustrate the problem of applying a deterministic search (Darwinian Machine) without integrating the transformative characteristics (Bernard Machine) of the matter. If an evolutionary algorithm search is initiated by a given fitness function, which applies copper to a façade to improve solar energy absorption, the findings may be flawed. The reason is that, as was shown in an earlier chapter, copper is transformative in terms of its visual expression and emissivity characteristics [Fig. 5.12], as a function of time and the local climatic environmental conditions. This indicates that a fitness function formulated in the

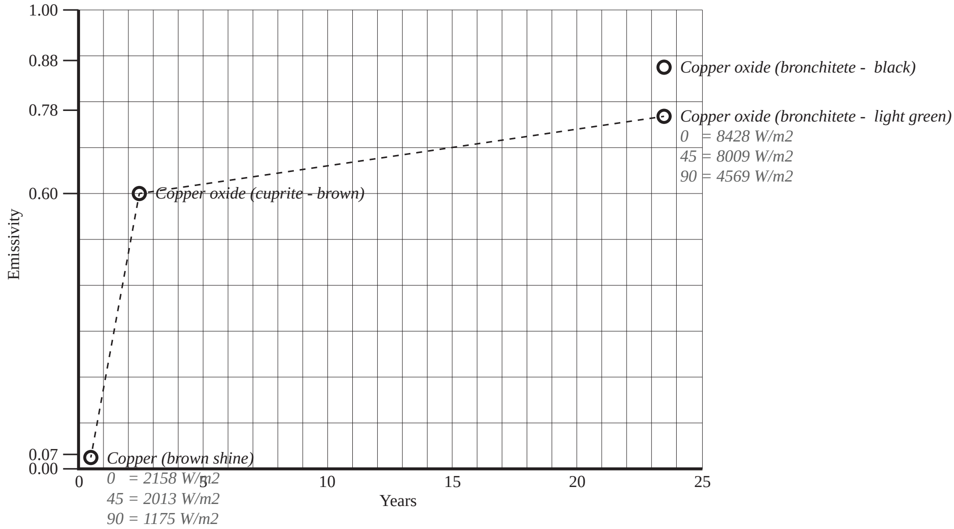


Figure 5.12

Diagram of copper emissivity development as a function of time and environmental conditions. Copper can serve as an applied example to the theoretical conditions shown in the previous diagram. Diagram by Isak Worre Foged.

design process using evolutionary algorithms should take into consideration the complexity of the matter organisation processes, as advocated earlier, to determine an informed search. Otherwise, the objective of the search may be unsound due to the steady-state assumption.

This condition can be implied to be the case for all transformative processes listed in the previous chapter. Conversely, this means that the transformative characteristics of matter (material-environment) may inform the Darwinian evolutionary procedure of selecting the fittest candidates for the next generations [Fig. 5.13].

As evolutionary biological models have been defined based on neo-Darwinian concepts and Mendelian genetic mechanisms, the Lamarckian theory of evolution was dismissed (Turner 2007; Turner 2012). The core idea of acquiring evolutionary characteristics based on processes occurring between gene mixing has, however, had a conceptual framework and terminology proposed by evolutionary biologist Conrad Waddington, who in 1940 formulated the concept of *Epigenetics*. The prefix 'epi', with the meaning 'beyond', consequently suggests an idea that exceeds the classical understanding of genetic processes. Waddington defined epigenetics as *'the branch of biology which studies the causal interactions between genes and their products, which bring the phenotype into being'* (Goldberg et al. 2007:635). More specifically, it can be formulated that *'epigenetics may be defined as the study of any potentially stable and, ideally, heritable change in gene expression or cellular phenotype that occurs without changes in Watson-Crick base-pairing of DNA'* (ibid: 635).

The theoretical model of epigenetics is relevant both to evolutionary biology and to evolutionary architectural design processes, as it identifies and starts the conceptual and potentially applied method for integrating adaptive building dynamics into an evolutionary design model. This addresses the transformative 'problem' above, exemplified in a simple manner by copper's transformative processes, as a potential for local specificity and ongoing articulated Environmental Tectonics. Additionally, evolutionary scientist Rene Thom makes a remarkable statement, in the context of this thesis, on Waddingtonian evolutionary concepts as he asserts:

> *I am inclined to think that the distinction in between embryology between 'genetic' and 'epigenetic' events is a moot question (perhaps as ill-defined as the classical problem of distinguishing inherited and acquired characters). I suspect that the only pertinent question to raise has to do with causal mechanisms. If you were to follow Aristotle's theory of causality (four types of causes: material, efficient, formal, final) you would say that from the point of view of material causality in embryology, everything is genetic – as any protein is synthesised from reading a genomic molecular pattern. From the point of view of efficient causality, everything is also 'epigenetic', as even the local triggering of a gene's activity requires – in general – an extra-genomal factor. (Thom 1989:3)*

These concepts of evolutionary processes, the ability of external factors to act on genetic processes, extending Darwinian concepts with Lamarckian concepts of evolution, seems to gain substantial support in the latest evolutionary biological

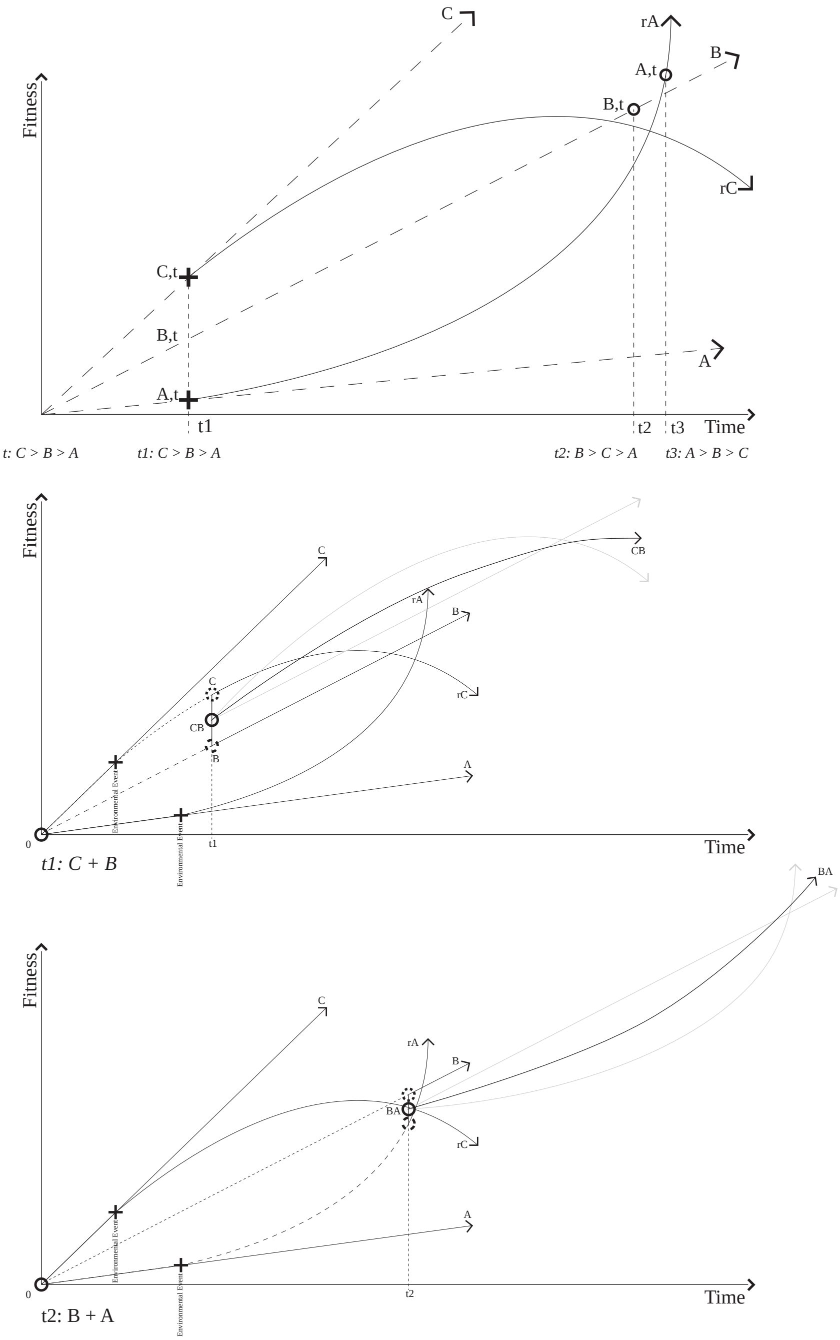


Figure 5.13

In dynamic conditions, relations between factors alter and form different conditions for determining fitness properties between solutions. The top diagram illustrates the changing fitness over time for different values. Hence, the combination of candidates are related to their time-based relative fitness description. The bottom two graphs illustrate the different fitness ascent according to combination strategy. Diagram by Isak Worre Foged.

research investigating how genes can be influenced during the life of an organism (Holliday 2006; Berger et al. 2009). More importantly to a matter-based architectural approach, the processes do not necessitate an organic organisation over an inert one to make use of the instrumental combination of Darwinian and Bernard machines in Waddingtonian epigenetic processes, as shown by the example of the use of copper. And, by previously formulated statements and by the reference to Thom and to the Aristotelian four causes, evolutionary principles in the most extensive sense of the word are conceptually, as well as instrumentally, connected to the Heideggerian notions of appearance, a principal notion in architecture in general, and in Environmental Tectonics in particular.

Before correlating the notions, arguments and fields further, pre-addressing the arguments of the next chapter, it can be noted that architectural theorist Sanford Kwinter has proposed that architecture could conceptually follow the form of the Waddingtonian model, in which the dynamics presented earlier are present. Kwinter posited:

> *Among the most powerful geometrical concepts invented to depict the relation between phenomenal forms (phenotypes) and the morphogenetic fields in which they arise is Conrad Waddington's concept of the 'epigenetic landscape.' The epigenetic landscape is an undulating topographical surface in phase space (and therefore a descriptive model, not an explanatory device) whose multiplicity of valleys corresponds to the possible trajectories (shapes) of any body evolving (appearing) on it. (Kwinter & Boccioni 1992:63)*

And:

> *Assuming that there exists at all levels of nature a principle corresponding to the path of most economic action or least resistance (which is only a misguidedly negative expression of the deeper principle that every action is nonetheless accompanied by its own sufficient conditions), the rivulets and modulations of the epigenetic landscape correspond to built- in tendencies, or default scenarios, that would condition the evolution of forms in the hypothetical absence of supplementary forces acting over time. But one should not be fooled into taking the 'form' of the epigenetic landscape as itself 'essential,' fixed, or predetermined. For it, too, is only a template, or virtual form, assembled in another dimension, as a multiplicity generated by an extremely complex field of forces. (ibid)*

Kwinter's primary argument is that the development of architectural form is not deterministic and continuously informed. It is influenced by all scales of development at all times. While these arguments clearly align with this thesis, Kwinter remains within the abstract notions of the model and does not offer an instrumental dimension to the theoretical concept that we attempt to address here.

5.5 Synthesis, Conclusions and Propositions

The core objective of this chapter is to identify, elaborate and exemplify an instrumentality of computation based on the earlier propositions presented. The questions presented in the preliminary section have been addressed by first outlining the basis for computational structures, which, as have been shown, has been a quest for computational science to produce developmental models, from the earliest concepts of John von Neumann, via Stephen Wolfram, to Ross Ashby and John Holland. While only touched upon briefly, cybernetics, as a field, is considered computational science by many (Steadman 2008) and thus partakes in the somewhat historical outline in Notes on Computation, which has been used as a necessary forerunner to the theory-building arriving at the argument of parallel and evolutionary mechanisms that are embedded into the propositions below.

Yasha Grobman et al (Grobman et al. 2009; Grobman et al. 2010) and Ali Malkawi et al (Malkawi et al. 2005; Malkawi 2005) observe and suggest, from the understanding that the design process has different phases and objectives within each phase, applying different algorithmic procedures to match these different criteria. The application of an evolutionary mechanism in architecture is therefore also in need of the agency of the architect to embed such processes. While Grobman et al and Malkawi et al consider the application of designated algorithmic processes to different phases, they do not address the central objective here, namely, to apply within the design process the algorithmic procedures that can be proposed for post-construction processes to accommodate an architecture that is still based on continuous environmental stimuli. The approach formulated above is based on the intent and notion that hybrid models can combine pre- and post-construct models, with the capacities to search architectural constructs prior to physical implementation and then continue their computational properties in a physical state during the ongoing building process. These arguments of computational instrumentality in relation to an Environmental Tectonic approach in architecture is believed to answer the research questions posed in the preliminary section to this chapter.

Based on the previous propositions and the arguments and answers presented here, the following propositions can be formulated.

Proposition 7
Evolutionary processes instrumentally empower an Environmental Tectonics approach.

Environmental Tectonics, as described in the previous propositions, can advance its potential through design agent-influenced evolutionary systems. First, this extends the capacity for processes of appearance by observable progression. Second, it allows an explicit integration of environmental aspects under organisational processes. Third, it supports the use of simple elements, a system and their formation. And, fourth, it makes use of parallel and distributed computational procedures, which extend both computational power and versatility of application.

Proposition 8
Epigenetic processes instrumentally advance an Environmental Tectonics approach.

Environmental Tectonics, being based on evolutionary processes, can advance through the hybrid instrumentality of epigenetic processes that extend the capacities of both the Darwin/Mendel and Lamarck/Bernard mechanisms towards a more complete integrative model for continuous matter organisation in architecture. This is proposed to allow an extended search for time-based environmental constructs and thus an extended instrumentality for the ongoing construction of human-perceived sensations.

6

Correlations

6.0 Preliminary

The previous three chapters began with an etymological and field-specific prolegomenon based on the objective and research questions described in the Introduction chapter. By identifying, examining and formulating a theoretical argument and answers within each field, a series of propositions have been offered as a basis for Environmental Tectonics. Within the chapters, inter-field relationships have been identified and, moreover, elaborated upon through theoretical arguments and case-based examples. With the attempt to further specify and elaborate upon these relationships and extend the answers given, three aspects that are identifiable by correlation are further discussed below. These aspects are emphasised to partially conclude, advance, explore and clarify the tentative grounding of the theoretical and instrumental framework. The three core aspects forming the expanded formulation for Environmental Tectonics, which have been previously discussed to some degree, are referred to as Aesthetics, Organisation and Evolution.

6.1 Aesthetics

Today, an architectural aesthetic is widely understood to be related to the organisation of parts in relation to proportions and the balancing of ordered and chaotic assemblies – the visually understood object (Steadman 2008). This notion of an architectural aesthetic is based on Greek philosopher Plato's thesis on beauty and form, relating the notion of beauty to objects (Böhme, 2010:24).

> The linking of being-beautiful and being-good in Plato has far-reaching consequences. It is already clear in his own work that, according to his definition of beauty, mathematical objects and, more precisely, geometrical ones, are the most beautiful. For nothing is as good, as precisely what it is, as a mathematical object: a sphere, a tetrahedron, a cube, a square, an equilateral triangle. Beauty thus becomes regularity, harmony, proportionality. (ibid: 25)

Kenneth Frampton, in his lecture *Reflections on the State of Things*, points to two forms of beauty as a rejection of the idea of a universal proportional system for beauty, one being positive (global), including three keys – richness of materials, precision in execution and symmetry understood as holism – and the other being arbitrary (local): modifications of positive 'keys' (Frampton 2011). Current writings on beauty and aesthetics as understood by visual form continue, even if the aesthetic visual form has moved beyond perfect platonic geometries. David Leatherbarrow suggests that the sublime and beautiful can be found between forms when contrasted, such as when roughness and smoothness meet in a sublime image (Leatherbarrow 2009:95). This aesthetic orientation comes closer to the Kantian aesthetic definition that is liberated from the Platonic precision of mathematical descriptive forms, and related more to the objects of everyday life (Böhme, 2010:27). Or, as stated by the American poet Ralph Waldo Emerson: '*The standard of beauty is the entire circuit of natural forms – the totality of nature*' (Emerson 1971). The notion of beauty and aesthetics is principally understood across the sciences by the object, even if it is imperfect, similar to the description by Leatherbarrow, within the Kantian orientation. From an art of engineering perspective, looking to natural forms, Julian Vincent asserts:

> *Although recognized as 'beautiful', biological structures are often stigmatized as 'imperfect', by which it is usually meant that they are asymmetric or irregular and of a complex shape whose functioning is not immediately apparent. Examples are curved bones, an asymmetric leaf, a gnarled branch. Maybe they appear to break easily, or even to encourage fracture, or take loads to one side. I shall show that these are characteristics not of 'imperfection' but of design for durability, and suggest that in an uncertain world, survival is more beautiful than symmetry. (Vincent, 2006:309)*

Additionally, the Dutch architect and theorist Rem Koolhass, in his curation of the Venice Architectural Biennale 2014, suggests that architecture return to the fundamentals. He lists the fundamentals as 'floor', 'wall', 'ceiling', 'roof', 'door', 'window', 'façade', 'balcony', 'corridor', 'fireplace', 'toilet', 'stair', 'escalator' and 'ramp'. The listed fundamentals of architecture, including its aesthetics, according to the world leading architectural exposition, exclude environment as an active architectural element and as potential authorship to architectural construction on both material and immaterial levels. From above, it is indicative that the architectural aesthetic discourse remains oriented to the visible and to the object.

While the term aesthetic was devised in the 1750s by Alexander Baumgarten, it is based upon the much older Greek word for sensation, *Aesthesis* (Thomson 2014). Hence, the sense of the world, as discussed earlier, constructs the core of an aesthetic description from its etymological origin. This relates to the Heideggerian notion of aesthetics in that feeling the world, as an activity, is aesthetics, while the result is beauty. Translated from German to English by Iain Thomson, Heidegger posited:

> *What determines thinking, that is, logic, and what thinking comports itself toward, is the true. (Thomson, 2014)*

Analogously:

> *What determines human feeling, that is, aesthetics, and what feeling comports itself toward, is the beautiful. (ibid.)*

This is intelligibly understood and convincingly created in, among others, the *Weather Project* (2003) at the Tate Museum in London, by artist and architect Olafur Eliasson. Here, Eliasson immerses the observer in sensorial impressions by reconstructing sun and sky conditions. While constructed by technical means alone, rather than invoked by architecture and outer environmental conditions, as proposed earlier, it illustrates the direct impact on the sensing human being. Architectural scholar Roger Scruton offers an extended argument on architectural aesthetics based on understanding the subject through the meeting between something perceived and the human imagination (Scruton 2013). While this relates to the notions of perception inherited from Uexküll, by the Funktionskreis, a difference from the argument approached here can be stated, as Scruton seems to remain oriented towards the object as the basis for an aesthetic dimension in architecture.

In recent writings by Böhme, this aesthetic orientation is further formulated into the proposition of beauty as residing in the construct of atmospheres, which, in this thesis, has been previously articulated by the notion of environmental construction. Ideas from Goethe, Heidegger and Heschong fall into this perspective, to be found in Böhme's linking of human perception with beauty, context and existence; he asserts:

> *What is decisive for us today, when we use the word beauty, is whether a person or a thing, a scene or a place makes us feel that we are there, whether these things, people or scenes contribute to intensifying our existence. (Böhme, 2010:30)*

For, as Heschong reminded us, and as Hawkins explicated, creating the multi-sensorial observation of a context elevates our understanding of both objects and place. The extended etymological integration, as included above, therefore upholds the earlier proposition that Environmental Tectonics is aesthetics expressed by the organisation of matter.

Correlation between environmental notions and tectonic notions as formulated here consequently suggests an extended aesthetic activity by including more dimensions (more senses) as a means for architectural construction methods and models. Questions of environmentally sustainable constructs become, therefore, questions of aesthetic constructs. Hence, this suggests a repositioning of the current agenda, from that of an environmentally sustainable architecture focused on singular energy concepts (Moe 2013), to an aesthetics-oriented architecture based on environmental articulations. What this may afford is a way in which tectonics can be understood, both in terms of the visual dimension – observed by, for instance, the two notions of global and local characteristics as described by Frampton – and by appearance, enabled by aesthetics (sensing the world), as embedded into techné as described by Heidegger. Effectively, it can be suggested that Environmental Tectonics allows a unity of all the senses to form an advanced notion of aesthetics in architecture.

This may also identify a tentative alternative position to the classical 'object-subject' basis for perceiving aesthetics. An aesthetic that is environment-based and less positioned in the classical object-subject relation (Thomson 2014) integrates environment as a constituent into the articulation of aesthetics, hence a provision for an 'environment-subject' division. This aligns more closely with the cybernetic understanding of perception (again, sensing the world) and affords an alternative model for aesthetic constructions (towards beauty).

6.2 Organisation

It was initially hypothesised, then formulated as an answer and later articulated as a proposition that Environmental Tectonics is a matter-based practice. In the chapter on

Environments, it was shown how the constituent climatic factors, such as moisture, light, air and other gases, could be understood as building material. In the chapter on Tectonics, it was shown how constructions undergo continuous alterations based on explicit environmental penetration and events in the solid material makeup, such as wood, metals and stone, and the subsequent effect of these processes on architectural thermal aspects.

The transfer of matter (and energy forms), which has been understood at one point in time as construction material and at another as an environmental factor, illustrates the capacity to approach new environment-based architectural constructs. These may in turn offer a much more integrative and responsive building approach and operate together with its context, rather than as isolated entities. In architecture, Michael Hensel (Hensel 2013) describes a similar notion, terming the concept of continuous structures *Non-Discrete Architectures*. This is positioned somewhat in contradiction to the systems thinking of Herbert Simon, who argues for the general condition of *Decomposable Systems* (Simon 1996). The apparent ambiguity might be explained by a difference in conceptual framing. A building can be segmented into individual spaces at different levels, as a decomposable and hierarchical system. Robin Evans, in his *Rights of Retreat and Rites of Exclusion: Towards a Definition of the Wall*, elaborates upon this argument. However, that does not restrict transfer of moisture, for instance, between these spatial entities. Hence, it can be understood as a decomposable system with non-discrete physical characteristics.

This understanding of the organisation of matter is believed to support both the environmental proposition of a matter-based practice and the tectonic-proposed underlying instrumentality of Element, System, Formation that clearly is formulated as a decomposable system, but with the inherent characteristics of a non-discrete approach. This approach may also bypass the problem of combinatorial additive systems as stated by architectural theorist Stan Allen:

> *Comparing these field formations to the organizing principles of classical architecture, it is possible to identify contrasting principles of combination: one algebraic, working with numerical units combined one after another; and the other geometric, working with figures (lines, planes, solids) organized in space to form larger wholes. In algebraic combination, independent elements are combined additively to form an indeterminate whole. The local syntax is fixed, but there is no overarching geometric scaffolding. Parts are not fragments of wholes, but simply parts. (As Jasper Johns has remarked: 'Why take the part for the whole; why not take the part for the part?') Unlike the idea of closed unity enforced in Western classical architecture, algebraic combinations can be added onto without substantial morphological transformation. (Allen, 1998:251)*

In this sense, the organisational principle suggested here allows activation of both additive processes and transformational properties. This argument has already been discussed in a tectonic context, using Utzon's Kuwait Parliament. Here, the nearly algebraic additive organisation of parts is paired with the geometric variation of the courtyards inside these parts. In a similar manner, from an environmental and continuous transformational perspective, the Arup algae façade allows modules to be systematically organised, while the module content exhibits significant responsive capacities in both visual expression and energy transfer aspects. There exists, in this way, potential for segmented and bounded organisations, hierarchically arranged, that satisfy 'simple' assembly logics of architecture, but with embodied transformational properties. And they do so while remaining open to modifications by environmental actors, effectively pointing back to the environment as an articulator by different forces and their changing levels of influence over time. Hence, localisation of architecture and the human is asserted to increase an Environmental Tectonic approach, in contrast to the current understanding of tectonic assemblies (organisations) as based on gravitational force, which is perhaps the most uniform and anti-local environmental actor imaginable. What Environmental Tectonics also attempt to confront is an architectural proposition to the considerable critique of architecture, formulated as a problem in the Introduction chapter of this work, and previously formulated as a provocative statement by Sanford Kwinter as he posited:

> *Increasing refinement of engineering and machining tolerances and increasing refinement in manufacturing and processing techniques allowed 'intelligence' or cybernetic capacity to become more and more generalized throughout the living environment. At the level of agency, the distinction between matter, design, machine, system, routine, civilization, and universe was collapsing. But if engineering for the advanced air-ocean world (mobile or non-gravity-based structures) increased the general quotient of distributed intelligence, engineering for the primitive gravity world (architecture and its prehistoric cult of 'compression' tectonics) remained a force of active stupidification. Even today the most finely crafted buildings rarely even begin to approach the refinement of facture or level of interrelatedness of a Ford Model T, let alone a nuclear submarine or supersonic aircraft.*
> *(Kwinter, 2007a[1997]:60)*

While the objective here is to construct an environmentally integrative theory, methods and models, it does not necessitate the making of complicated architectural systems, as is the first answer in much architectural research and practice today (Moe 2010). On the contrary, as has been argued towards the formulation of the Element, System, Formation instrumentality, the organisation of a design methodology with specified and hierarchical properties may advance beyond the contemporary complicated architectures by using extensive geometrical complex structures. This statement aligns with the examination of architect Louis Kahn's Salk Institute by Kiel Moe, who suggested:

> *When observed as an integrated system in operation over time, the building is a poignant demonstration that complex architectural performance can—and perhaps can only—emerge from a seemingly simple compositional logic.*
> *(Moe 2008)*

6.3 Evolution

In Semperian terms, the transformation of an artefact by continuous discernible modification, Stoffwechsel, helps the observer to read and understand the meaning of the artefact. It relates to the four causalities, from Aristotle, as reintroduced by Heidegger for the grounding of tectonics and as the crucial objective of architecture as a vehicle of revealing for humans. The modifications are developmental steps from one state to the next. It is an evolution of the artefact by the agency of the maker. Heidegger offers another term, *physis*, which, in contrast to techné, is making by natural processes (Heidegger 1977). In correlating the notions provided in the three previous chapters, it can be argued that Environmental Tectonics may afford a combined form of agency, that which is related to the architect, and that which is related to the natural and environmental processes, driven by both the Darwin and Bernard machines.

French philosopher Gilles Deleuze suggested, in congruency with previous arguments, that evolutionary processes in technology and culture are influenced by gradual isolated progressive steps, 'singularities', and the influence of environmental and material properties as evolution takes place as 'traits of expression'.

> *Let us return to the example of the saber, or rather of crucible steel. It implies the actualization of a first singularity, namely the melting of the iron at high temperature; then a second singularity, the successive decarbonations; corresponding to these singularities are traits of expression – not only the hardness, sharpness and finish, but also the undulations or designs traced by the crystallization and resulting from the internal structure of the cast of steel. The iron sword is associated with entirely different singularities because it is forged and not cast or molded, quenched and not air cooled, produced by the piece and not in number; its traits of expression are necessarily different because it pierces rather than hews, attacks from the front rather than from the side ... We may speak of a machinic phylum, or technological lineage, wherever we find a constellation of singularities, prolongable by certain operations, which converge, and make the operations converge, upon one or several assignable traits of expression. If the singularities or operations diverge, we must distinguish two different phyla: that is precisely the case for the iron sword, descended from the dagger, and the steel saber, descended from the knife. But it is always possible to situate the analysis on the level of singularities that are prolongable from one phylum to another, and to tie the two phyla together. At the limit, there is a single phylogenetic lineage, a single machinic phylum, ideally continuous: the flow of matter-movement , the flow of matter in continuous variation, conveying singularities and traits of expression. (Deleuze & Guattari, 1987:406) (DeLanda, 2001:137)*

Within the above philosophical example of making, environment, matter and gradual progression are combined in the construction of the artefact. This forms an organised 'mixed string of activities' that is both experimental (stochastic) in method and goal-oriented (deterministic) in its objective.

Evolutionary models integrating end exhibiting the dynamics of the built environment may in this way serve as the instrumentation of both a prescriptive (as argued in the previous chapter and above) and a descriptive method to better observe and understand architecture's modalities and its relationship to its environmental context. Researchers in actor network theory Bruno Latour and Albena Yaneva state:

> *Everybody knows – and especially architects, of course – that a building is not a static object but a moving project, and that even once it has been built, it ages, it is transformed by its users, modified by all of what happens inside and outside, and that it will pass or be renovated, adulterated and transformed beyond recognition. We know this, but the problem is that we have no equivalent of Marey's photographic gun: when we picture a building, it is always as a fixed, stolid structure that is there in four colours in the glossy magazines that customers flip through in architects' waiting rooms. If Marey was so frustrated not to be able to picture in a successive series of freeze-frames the flight of a gull, how irritating it is for us not to be able to picture, as one continuous movement, the project flow that makes up a building. (Latour & Yaneva, 2008:1)*

From architectural, computational, philosophical and biological perspectives, an evolutionary procedural approach appears to exist for architectural production in general and seems instrumental to the specific objective of an Environmental Tectonics orientation in particular. The above statement by Latour and Yaneva supports the previous suggestion of epigenetic evolutionary models, in which an architectural process of making is not bound by a pre-construction design, but entails the ongoing making and appearance. Hence, an epigenetic architectural model is believed to exceed the current approach of architectural computation, which follows the common practice of architecture to describe the design until its construction and then leave it without any intention of further articulation. By asserting that environment acts on the tectonic qualities of architecture and that environment is at all times present, the ability to compute time-active architectures is perceived to enable the architect to conceptualise and construct beyond current practice.

Through this, it is proposed that architectural epigenetic models, situated in the scope of Environmental Tectonics, can reach new levels of aesthetic articulation. This in turn serves the objectives of increased human perceived sensation for an advanced architectural aesthetics and the decrease of energy forms that damage the climate for the benefit of the natural environment in which humans are so intimately connected.

5.4 Synthesis and Conclusions

The intention of this chapter was to elaborate upon arguments, research answers and partially conclude the notions and statements provided in the previous three chapters with the subsequent aim of identifying and proposing correlations that extend the theoretical argument of the thesis. By correlation, three principle aspects were formed and argued to be central in an Environmental Tectonics approach to architecture. Aesthetics, Organisation and Evolution are, in this way, understood both as theoretical constructs and as instrumental means for constructing environmental architecture.

Two predominant orientations to environmentally sustainable architecture have been discussed. These are an environmentally open (FRB and POA) and an environmentally closed orientation (PH and ZEB). Environmental Tectonics based on open and integrative methods positions itself away from the isolation/insulation orientation of the Passiv Haus and Zero Energy Buildings approaches. Instead, it aligns with several ideas and intentions of the orientation, including Free-Running Buildings and Performance-Oriented Architecture. However, rather than categorise the thesis within either of these two approaches, it has, from a theoretical perspective, been attempted to formulate an orientation that is distinct in relation to the initial research questions. Specifically, it is argued that Environmental Tectonics, through a theoretical repositioning of tectonics, is distinct in that:

(1) Environmental Tectonics proposes explicit methods for constructing human sensations oriented towards an environment-based aesthetic articulation in architecture.

(2) Environmental Tectonics proposes an explicit prescriptive design methodology towards environmental architectural tectonic organisations.

(3) Environmental Tectonics proposes the integration of Semperian Stoffwechsel by way of progressive constructions aiding continuous appearance between humans and the environment.

The aim of part two, with its four main chapters, was to mount a tentative architectural theoretical framework for Environmental Tectonics as an approach to environmental sustainable architecture. Within this, concrete instrumental methods are suggested and elaborated in the context of the objective, problems and research questions presented within the Introduction chapter. Rather than devising specific guides to be followed, the theoretical and instrumental propositions have been formulated as an attempt to construct an adoptable and adaptable approach. The propositions and their expanded arguments within this chapter, based on the terms aesthetics, organisation and evolution, serve in turn as the provisional platform for design research explored in the third part of the thesis, Probes. As stated, these studies have been an integral part of the theory building presented above in part two, but are nevertheless developed in progressive steps in themselves, following the overall research design method of questioning, theorising, testing by computational and analogue prototypes and re-questioning.

7

Acoustic Tectonics I

I find it's a beautiful thing when you make the building a quiet place. That's pretty difficult these days, because our world has become so noisy. Well, not so much here, perhaps. But I know other places that are much noisier and you have to go to some lengths to make quiet rooms and imagine the sound they make with all their proportions and materials in a stillness of their own.

(Zumthor, 2012:31)

7.0 Preliminary

Following the objective of this thesis, to formulate and construct methods and models for an human-oriented environmental sustainable architecture, it is relevant to study the omnipresent aspect of sound in relation to architecture – architectural acoustics. Such work ties the human listener, the sound environment and the materialisation of architecture together, as formulated by architectural theoretician Steen-Eiler Rasmussen (Rasmussen 1964). Swiss architect Peter Zumthor elaborated on the subject of sound in relation to architectural articulation. Architecture is, from this perspective, not only the means of amplifying a given sound environment; it may also support the effect of diminishing sound, as stated above. Or, as is studied in this chapter, the materialisation of architecture can work to neutralise the aspects that may alter the sound created by the musician. Commonly, architectural musical spaces are created to amplify and support the sound that is created to extend the amount of time for which it can be aurally perceived in a space. It becomes an acoustically lively space by this approach. In contrast, music created and recorded for later application in a space through loudspeakers has been tuned so that the effect of the music is created when it leaves the loudspeaker. From this perspective, the architectural acoustics need to become neutral so as to allow the sound-based environmental experience to become the one the musician intended.

The background on the previous solutions is found in the studies by Sato et al (Sato et al. 2004), Brady Peters et al (Peters & Olesen 2009) and Alberto Pugnale et al (Pugnale 2009). These studies, as previously discussed in chapters 1 and 3, all apply computational simulation procedures of sound. Additionally, Sato et al and Pugnale et al pair the simulations with computational search procedures based on genetic algorithms.

The studies above have focused on aspects related to either the surface patterning or the development of the overall acoustical space. The background for potential solutions lies in the combination of these aspects, using an evolutionary algorithmic search method combined with an analytical simulation method for the overall spatial geometry and a ray-tracing simulation method for the articulation of local articulations of the space.

From this, it was attempted in this study to create a design method that combines simulation methods, assessing two acoustic properties driven by evolutionary processes. Additionally, rather than developing an architecture based on one sound source, as is common in concert halls and lecture halls, the study includes four sound emitters that, in combination, are the source for the sound environment. To allow a combination of global articulation and local differentiation based on elements and their joint formation, a parametric model is created that integrates both sound simulations and evolutionary simulations.

The chapter presents methods and models based on the Element, System, Formation instrumentality, sound-perceived environmental simulations and progressive design development based on genetic algorithms. From a series of studies based on this experimental setup, results from this approach are presented, followed by conclusions and discussion.

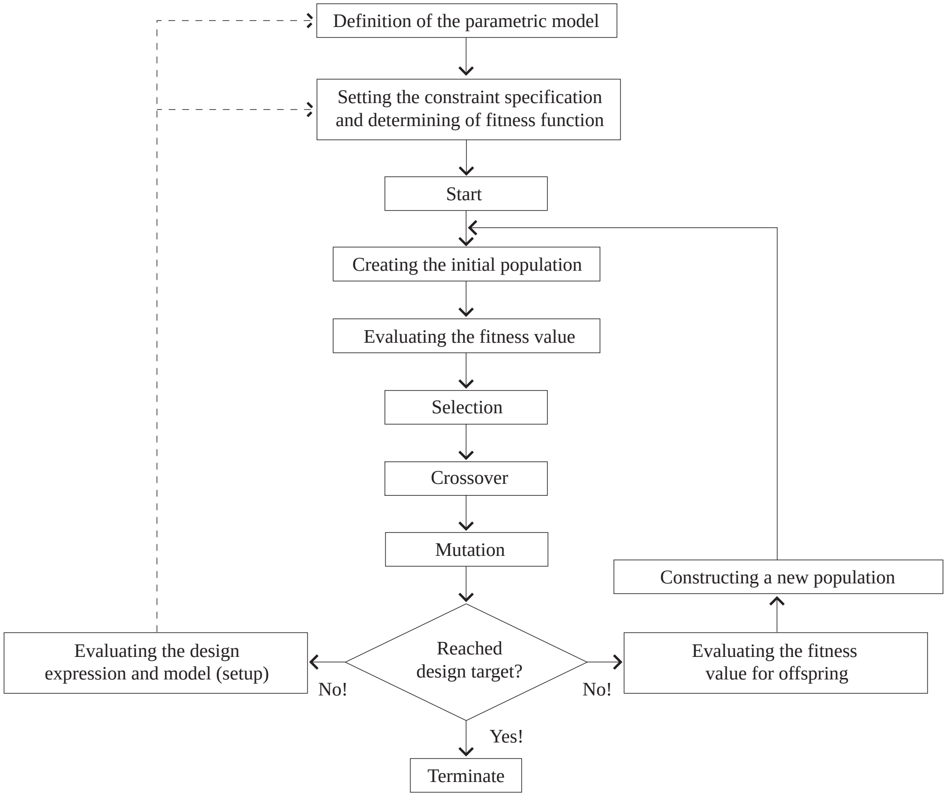


Figure 7.1

Diagram of the evolutionary design process based on a cyclical design model. The model includes the parametric design model and the semi-automated possibility to change the parametric constraints within the design process. Diagram by Isak Worre Foged.

7.1 Methods and Models

The study integrates three distinct models that, in combination, form the integrative architectural model. These are the evolutionary model, the environmental simulation model and the parametric model.

Evolutionary Model

As described in the chapter on Computation, there are three essential operational parameters for a designer to develop and describe when working with genetic algorithms. These are a (1) description of the fitness function, (2) definition of the variables of the population and mutation rate, and (3) conversion from genotype (logical system) to phenotype (physical design). The progressive design model [Fig. 7.1] is based on the cyclical integration of sound assessment and the parametric model boundaries as prescribed by variables. By focusing the study on a method and model for sound-based architectural morphogenesis, a standard genetic algorithm (SGA) is applied through the Galapagos Solver, developed by David Rutten at McNeel Software (Rutten 2013). The design of the fitness function – that is, what to search for – is instead uniquely defined as based on the sound simulation integration.

Environmental Simulation Model

The twofold simulation, assessing overall spatial geometry and local surface articulation, is based on simulating the perceived reverberation time and the ability of local surfaces to modify reflections, influencing the sound scattering within the space. Within this study, the Sabine equation [Eq. 7.1] is used as an empirically proved method for high-reflective materials and spaces (Long 2014). While it is a simple measure for the specific acoustic quality, the equation is widely used. Also, as previously argued, this enables a fast computational assessment, allowing a rapid iterative process for early architectural design phases. Its simple relationship between volume (V), surface area (S) and material absorption coefficient (A_t) defines the time from which the sound pressure decreases by 60 decibels (dB) after the sound source is terminated, noted as RT60. The Sabine equation is formulated as:

$$T_{60} = 0.161\frac{V}{A_t} \tag{7.1}$$

The ray-tracing algorithm is based on a calculation of the reflective angles of the spatially straight sound rays. Due to a small difference in the surface structure of the material, a scattering mechanism modifying the computed reflective angle is included.

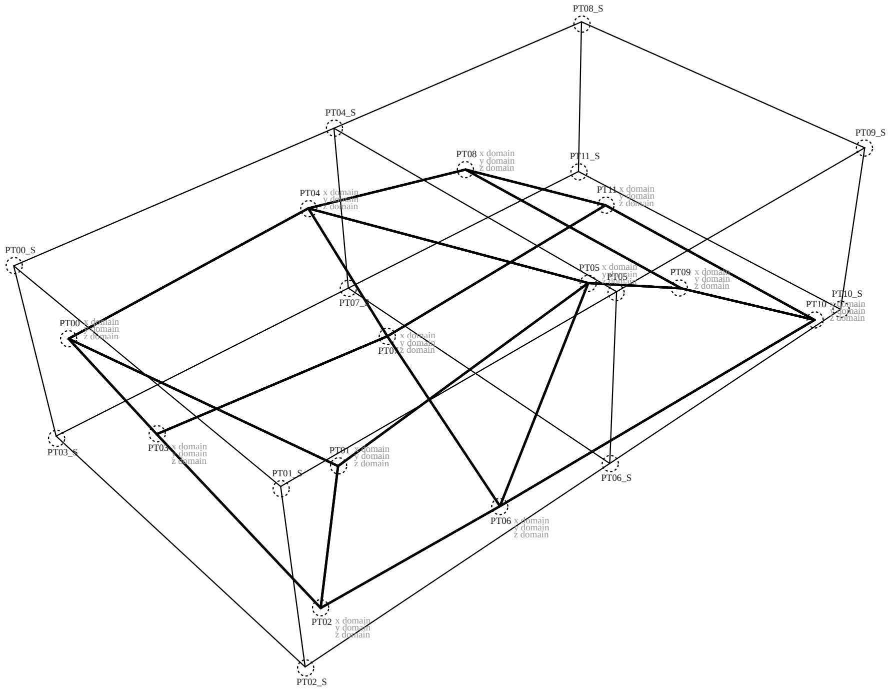


Figure 7.2

Parametric model of the global spatial geometry with 12 control points each defined by a set of x,y,z variable bounds. Diagram by Isak Worre Foged.

Parametric Model

The parametric model, the environmentally embodied phenotype of the evolutionary model, is based on two operational design levels, global and local. The global level is defined by twelve control points, which are defined by three numerical domains, representing the variables of the x,y,z coordinates [Fig. 7.2]. This allows the designer to influence an inner and an outer space, which enables the relation of the development of the volume to a project-specific site and the human scale.

The inner surface of the volume is defined by an array of elements. These are spatially defined by the global model at their four-point base positioned on the global model surface [Fig. 7.4]. The element is further defined by five additional points: a centroid and points located between each of the four points connected to the global model. The point defined by the centroid has freedom of movement in x,y,z dimensions. The four points located between the four base points have freedom of movement from the boundary of the element base plane and towards the centroid of the element. This allows the local element to spatially modify from a flat surface to an advanced eight-sided pyramid shape defined by planar parts. The material used for the study was 6 mm pine plywood with an absorption coefficient of 0.1 at 500 Hz.

7.2 Design experimentation

The combined methods listed above are then applied as an architectural design methodology in the form of an application illustrating an environmental tectonic approach. By progressive steps, observable to the designer, the articulation of an acoustic-based envelope is developed. The design process is cyclical through the below procedure, following figure 7.1.

(1) Searching volume by evolutionary processes to ‘neutralise’ external acoustic influencers

(2) Searching reflector by evolutionary processes to ‘neutralise’ external acoustic influencers

Studies are done in the order stated above and by combining (1) and (2) to explore the effect on the progressive process.

Searching for volumetric articulation follows the methodology described above, with the fitness function being used to determine a minimum reverberation time. This is based on the previously stated condition that electronic music is unconventional in the way that it is spread via loudspeakers, rather than non-amplified instruments. The music is acoustically developed to produce the best sound possible within the loudspeaker cabinet. The pavilion therefore searches for the minimal effect on the sound but the maximum protection of the clear sound, thus eliminating the reverberation time. The definition of the volume domain, the algorithmic search field, is determined by the site contextual setup. The contextual setting at the harbour front in Aalborg is used to

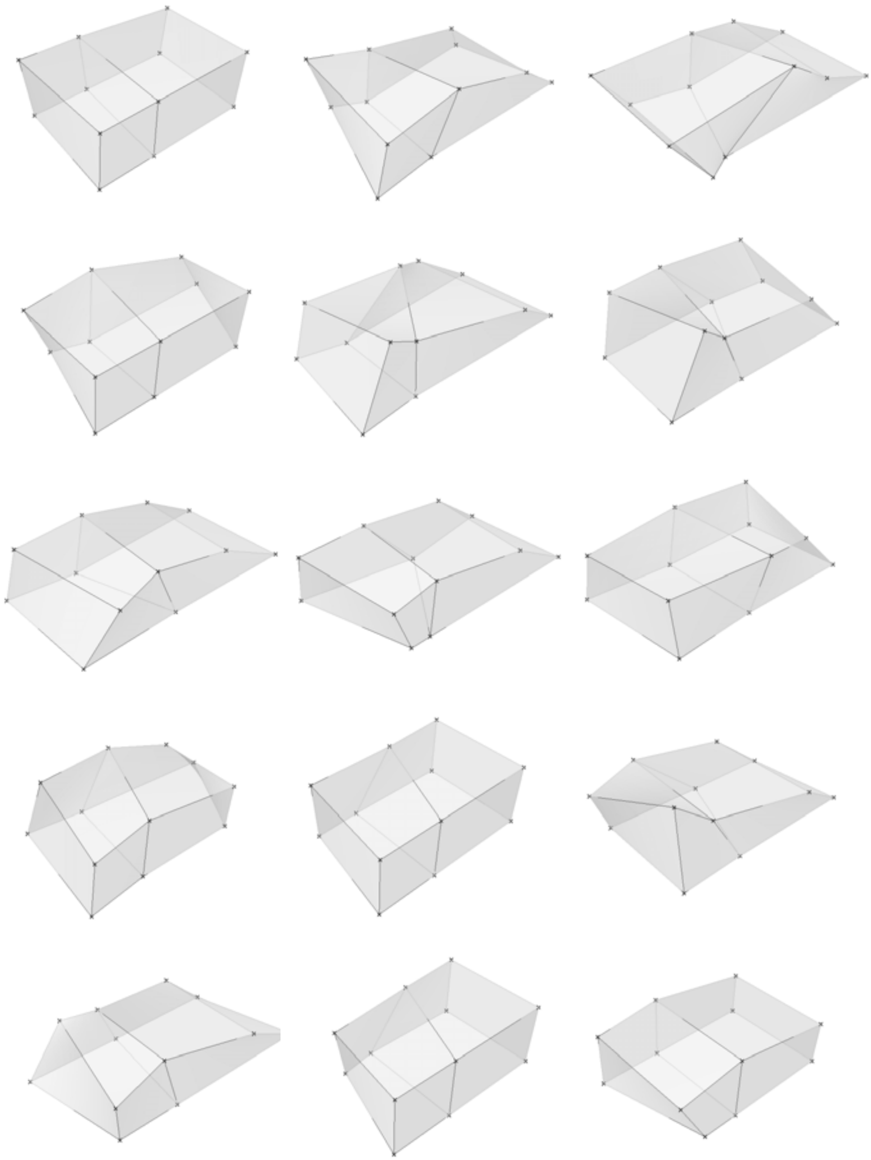


Figure 7.3

A series of design generations created from altering the phenotype's organisation by evolutionary processes towards a higher acoustic articulation in relation to the specified electronic music. Screenshot of compuattional model by Isak Worre Foged.

create a boundary for the algorithms to evolve within, considering a clear orientation to the space towards the waterfront as a specific characteristic that will set the spatial architectural scene. The evolutionary search model and its variables are defined by:

$$Acoustic\ Tectonics\ 1_{global}\begin{cases} Minimise & f_{(x,y,z)} = RT \\ subject\ to & -10 \leq x \leq 50 \\ & -50 \leq y \leq 50 \\ & 0 \leq z \leq 50 \\ Mutation\ rate & 0.2 \\ Population\ size & 100 \end{cases}$$

Searching reflector organisation is done with the intention of articulating the architectural acoustics explicitly, making a sensed space based on sound aspects. Reflection of the sound is aimed at (1) creating the maximum number of reflections between the reflectors without sending the rays back into the listening space or (2) directing the sound rays away from the pavilion. Both strategies seek a clear, low reverberation time for electronic music. The external sound environment of the acoustic envelope is based on the site conditions, with a sound void, the Fjord, and high noise levels from the road. By searching for a reflector that shields the space from external noise while absorbing the sound rays, the evolutionary procedure integrates the omission of potential sound rays from the locations of the road while being open to the sound void constructed by the Fjord's open spatial plane. The applications of these aspects are studied in the four models below, in response to which the eight-sided pyramid element form can change. The variables include (a) the length of the normal vector to the surface, (b) the length of the vector from the surface to the sound source and (c) + (d) studies of the first two, but with an allowance for variation in the directionality of the vectors towards a source of the normal vector to the global model surface. The evolutionary search model and its variables are defined by:

$$Acoustic\ Tectonics\ 1_{local}\begin{cases} Maximise & f_{(v_a,v_x,v_y,v_z)} = Reflections \\ subject\ to & 5 \leq v_a \leq 50 \\ & -10 \leq v_x, v_y, v_z \leq 10 \\ Mutation\ rate & 0.2 \\ Population\ size & 200 \end{cases}$$

Commonly, as mentioned above, acoustic spaces are defined by a single source or a group source located in the same area. The study explores the spreading of the sound source by implementing loudspeakers situated in each corner of the global spatial volume. Applying the model above is then used to identify the varied sound-source vectors from the emitters within the volume. This subsequently derives the complete geometrical organisation of the reflectors [Fig. 7.7]. The method and model allow a zone of reflectors to focus on a specific loudspeaker, to scale its geometry in order to alter the reflective factor (absorption level) and at the same time to open its geometry towards the water and close it off towards the road.

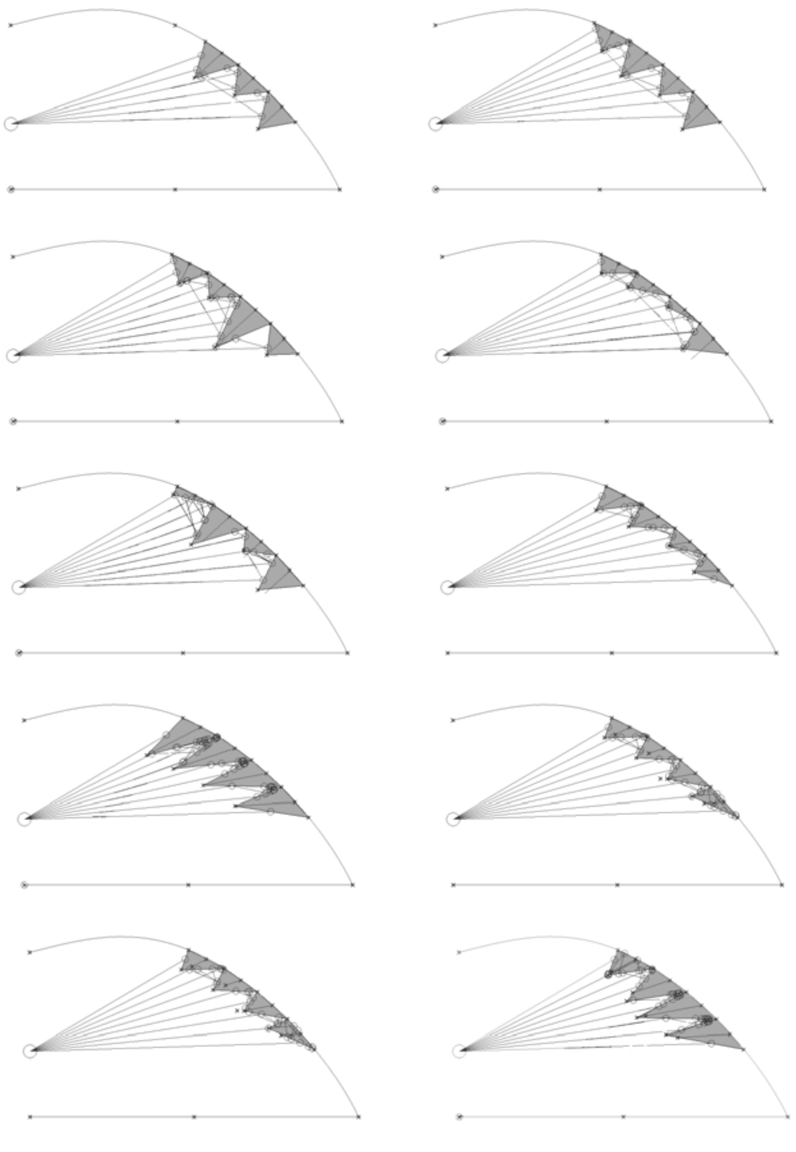


Figure 7.4

Study and evolution of a reflector geometry towards a maximisation of absorption. The study includes four different strategies (a,b,c,d), indicating the capacity of long stretched geometries oriented towards the sound source with slight heterogeneous variations across the elements. Screenshot of computational model by Isak Worre Foged.

7.3 Results

The work illustrates an approach to environmental articulation in architecture by the combined models of evolutionary processes, environmental simulation assessment and a parametric model that is based on an array of local elements that are combined into a global formation. By the dual approach of searching a global form and a local articulated surface, an environment is developed to make the desired impact on the listener through the electronic music.

Specifically, the work finds that:

(1) Evolutionary processes can be applied as an instrumental approach to advance an environmentally based architecture towards one that enhances specified perceived sensations for humans. In particular, the studies show a clear improvement of the reflection count (absorption by increased reflections) by using a sound source-oriented approach and a slight further improvement by allowing the vector that is oriented towards the sound source to deviate. The sound-based sensation simulated is, however, only based on a singular point within the model to decrease the complexity of the search space. In this way the study and result are based on exploring the reverse situation of the normal procedure of sound carried by single emitters to multiple receivers.

(2) The organisation of the parametric model as based on the Element, System, Formation instrumentality allows an operational capacity for both global and local form-finding in parallel. However, the definition of 200 elements, with each element based on five points of 'freedom' with a ten-number variable domain, restrains the computational iterative process for early design phases. The solution search space, despite being based only on three dimensions (x,y,z), is defined by 200^{50} combinations. To meaningfully explore and interact with both the problem space and the solution space as a design method, the evolutionary search process may benefit from reducing the variables or nesting the search procedure into a series of sub-procedures or concatenated studies. From this it is suggested that a progressive reformulation of the problem space is integrated into the model in order to target the evolutionary technique's search space without compromising the ability of stochastic search to move beyond design solutions that are obvious to the designer.

7.4 Conclusions

The study explores and exemplifies the articulation of environmental sensation by an evolutionary architectural design method. The four causes – causa formalis, causa materialis, causa finalis and causa efficiens – are then used to evaluate the Environmental Tectonic properties of the study.

The progressive design process, as argued above, reveals the formation process, causa formalis, in relation to the intention of environmental articulation. The

Figure 7.5

Musician playing inside the acoustic pavilion created from the computational experimental studies. The locally articulated elements behind the musician are formed according to the four sound sources. Photo by Isak Worre Foged.

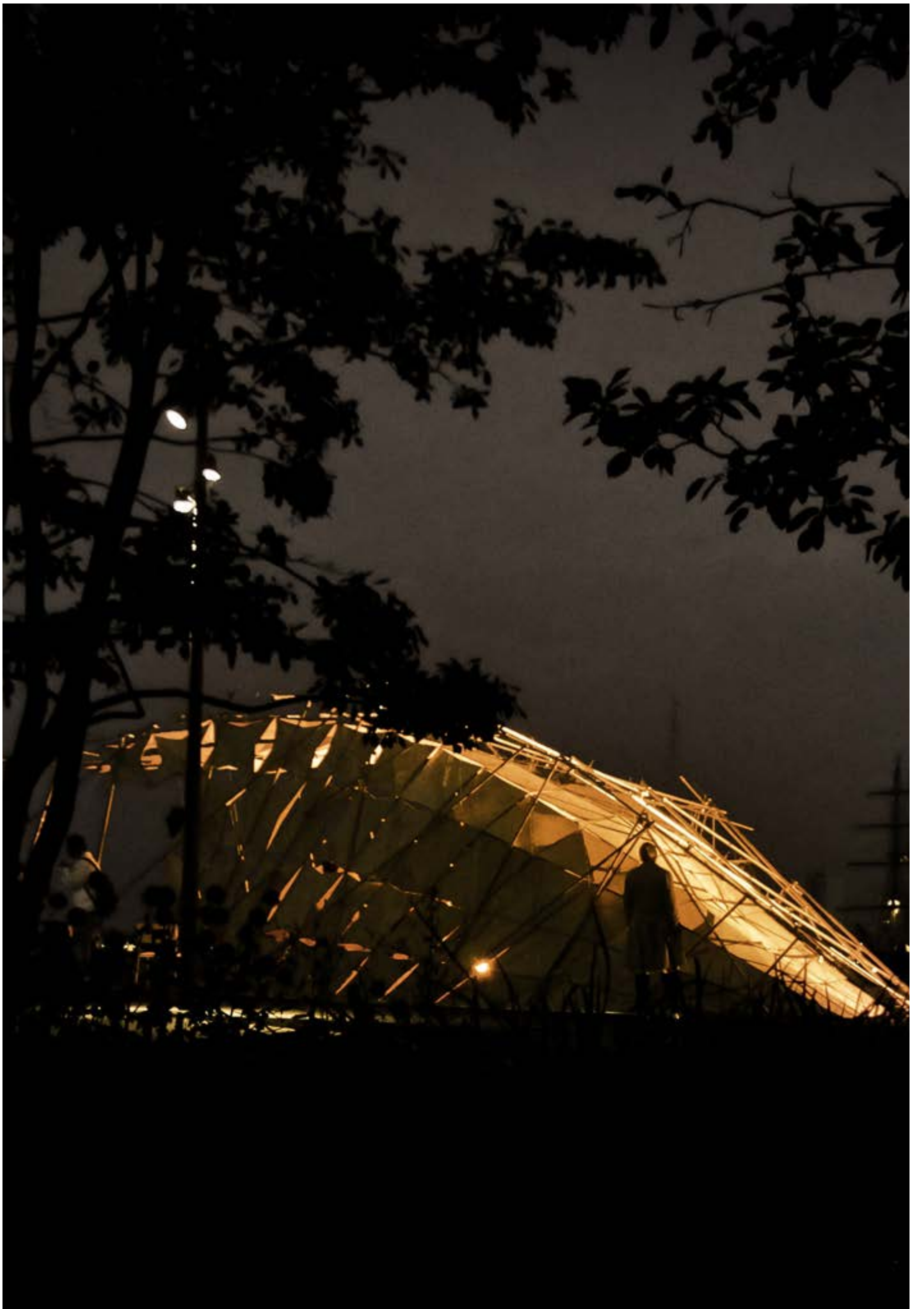


Figure 7.6

The acoustic pavilion from the outside, defined by its global geometry and smooth surface contrasting the inner reflective elements. Photo by Isak Worre Foged.

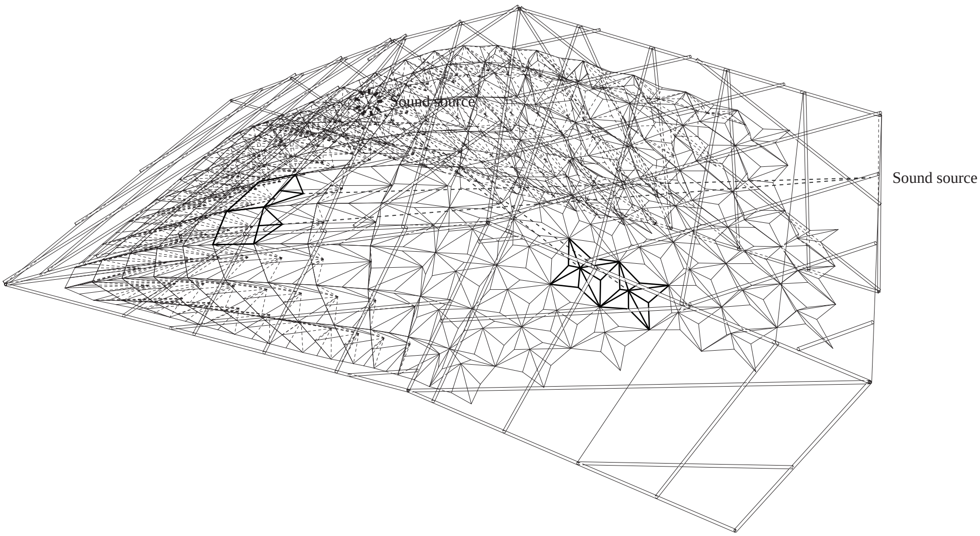


Figure 7.7

Drawing showing the effect of the algorithm in orienting the elements to different loudspeakers, scaling their reflective factor and opening/closing them towards their surroundings. Drawing by Isak Worre Foged.

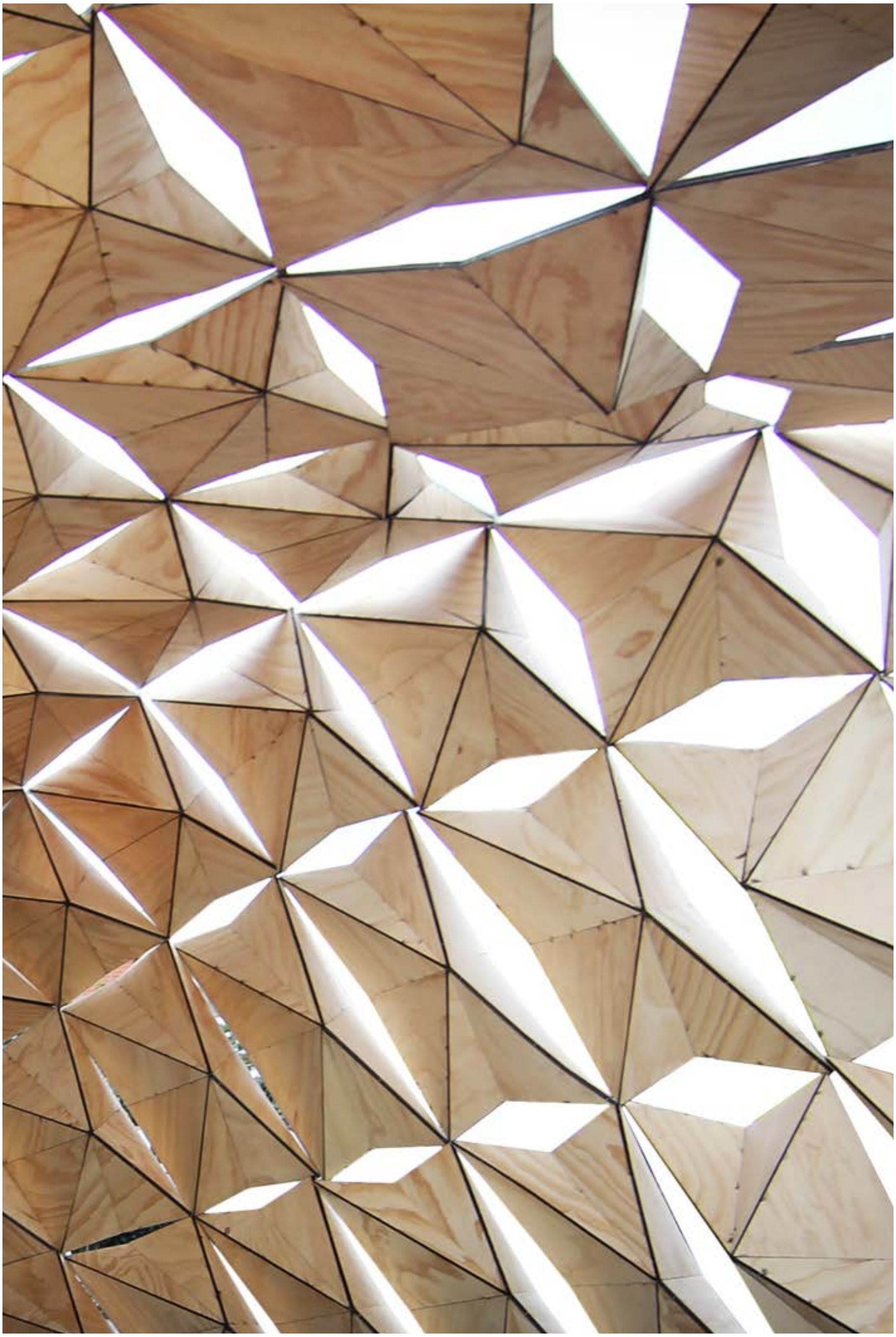
process is visible on both global and local formation levels, enabling the designer to perceive both the transformation of the initiating base geometry and the internal surface development. These processes, in turn, enable the designer to observe and modify the design variables defining the geometries. While the physical properties, causa materialis, of plywood include its sound absorption and reflective properties, its material capacity is not developed during design progression. The progressive process is based solely on gradual geometrical modifications. The model fails in this way to unfold the material capacity in relation to environmental articulation and thus reduces its capacity to reveal the environmental integration in full. The final form, causa finalis, is explicitly linked to the progressive design process, causa formalis, and the environmental effects of the probe, causa efficiens. The final form is perceived primarily from aural and visual sensation. While the visual form is static, it reveals a dynamic potential, as posited by Rasmussen, based on the constant audible dimension that is materialised by the causa materialis and causa finalis. Without the dynamic aural changes, the visual final form would decrease its meaning, being based ‘only’ on its visual and formal articulations on global and formal levels, as discussed in the chapter on Tectonics (chapter 4). The causal effect of the form, causa efficiens, is clearly present in direct relation to the causal effects of the form and its final capacities as an environmentally oriented architecture. However, as stated above, the environmental effect is oriented towards a single point of the space, reducing the general reading through sound to a limited area, and thus is limited in terms of its effect on multiple listeners simultaneously.

7.5 Discussion

With a total of 200 distinctive elements used to create the model developed by the design method, a high visual and audible resolution was achieved. The ‘cost’ of this resolution, however, is an extensive manufacturing process of unique parts. While the computational model was automated to output the production files for laser-cutting production, the 1900 parts needed assembling by hand. The ability to readily construct and manufacture heterogeneous parts enforces, however, the complexity of assembling a large quantity of elements with no margin of error. This approach is in opposition to the arguments of standardised parts, and, ‘minimum inventory - maximum diversity’. Much architectural research is currently advancing and promoting robotic assembly methods to overcome this problem. Another approach may be to construct parts that are easily assembled while maintaining advanced behaviour in relation to the environmental articulations. This provision has already been stated in the chapters entitled Tectonics and Correlations.

Figure 7.8

Electronic music performed in the pavilion during a cultural event in Aalborg, Denmark. Photo by Isak Worre Foged.



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8

Acoustic Tectonics II

Sight isolates, whereas sound incorporates; vision is directional whereas sound is omni-directional. The sense of sight implies exteriority, but sound creates an experience of interiority. I regard an object, but sound approaches me: the eye reaches, but the ear receives.

(Pallasmaa, 2012:53)

8.0 Preliminary

In the previous study, it was shown how a sound-based environment is able to construct architectural articulations based on evolutionary design processes. The study was directly related to the questions posed in the Introduction (chapter 1) and in Fields (part 2) of this thesis. Also, it was illustrated how evolutionary processes as a design method can exhibit progressive development through discernible modifications. The conclusion and discussion, however, also identified that, when evaluated against Heidegger's four causalities in relation to revealing, the matter dimension appeared less developed. It is, in this second study, appropriate to reinstate the previously referenced statement by Rasmussen, emphasising the material causalities, causa materialis, on sound-based environments in architecture, as he posited:

> *Can architecture be heard? Most people would probably say that architecture does not produce sound, it cannot be heard. But neither does it radiate light and yet it can be seen. We see the light it reflects and thereby gain an impression of form and material. In the same way we hear the sounds it reflects and they, too, give us an impression of form and material... (Rasmussen 1964)*

The causal effect of the material is revealed through the acoustic environment. Another aspect that was found problematic in the previous study was the extensive search space for early design phases. There was a suggestion in the conclusion to base evolutionary design processes on a reduced set of variables or form them through nested procedural applications, effectively segregating the design process into sub-search procedures. A third aspect was the specific location of the observer, limiting the sensation to people occupying the singular point that is assessed in relation to the developmental procedure. By the extended integration on the causality of materials as laid out above, the following question is formulated:

How can instrumental sound-based environments be articulated by evolutionary processes enabled by material-environmental relations towards environmental tectonics?

The background on the previous solutions is derived from the studies and findings provided in the previous chapter. This also includes the references to prior studies by Sato et al (Sato et al. 2004), Pugnale (Pugnale 2009) and Peters et al (Peters & Olesen 2009). Additionally, studies by Spaeth and Menges (Spaeth & Menges 2011) relate to the work by Pugnale and Sato et al with the objective of transforming large prescribed spaces through evolutionary algorithms. In a later study, Peters et al construct a 1:1 wall segment, exploring the effects of scattering but with the intention of directing the sound towards a singular point and shield of another zone with the same wall. The procedure, between analysis and modelling, is iterative but not automated as a looping progressive design system (Peters et al. 2011). A different yet related approach by Lim was to study a concert hall by applying an agent-based algorithm. In this study, a particular focus was placed on the large roof reflectance to improve the distribution of

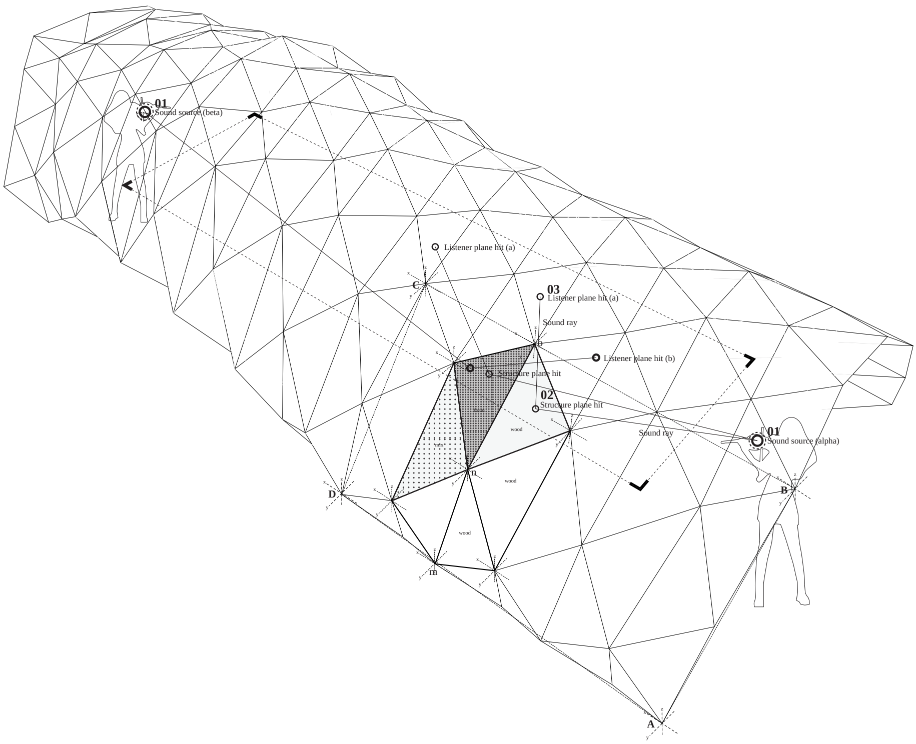


Figure 8.1

Drawing of the global and local space definitions illustrating the control points and their variable domains as defined by x, y, z coordinates, with additional variables defining the three material states of the model. Drawing by Isak Worre Foged.

sound across a deep space (Lim 2011). From this, a digitally modelled ceiling would change curvature as a way to physically modify the expression and properties of the sound-reflecting ceiling.

The background for potential solutions is based on an extended material integration. A second aspect is an extended search criteria that enables the development of a literal instrumental architecture that increases the relationship between the sound environments created by musicians, the architectural construction and the listener.

What is attempted in this study is to formulate a method and model in which classical musicians can use architecture as an extension of their instruments. This is approached by using evolutionary algorithms to search for an environmental-material organisation that allows the musician to change the acoustic environment by changing his position within it, so that the environment becomes instrumental for the musician based on her related spatial positioning.

The study presents a parametric model, a sound environment simulation model and an evolutionary model. The combination of these models allows the development of a digital and 1:1 physical probe, which investigate the notions of environmental constructions as formulated in the chapters within Fields (part two).

8.1 Methods and Models

The studies are based upon the combination of three computational methods and models: parametric modelling, environmental simulation and evolutionary computation. Combining these methods forms the instrumental setup that enables the design research investigations.

Parametric Model

The parametric structure defined is based on an origami folded structure that is changeable at two levels within the structure [Fig. 8.1]. The first level, global, is the overall folding form of the structure that is controlled at a series of control points, forming a ‘tunnel’ geometry. The control points have freedom of movement in x, y, z dimensions, but without the ability to overlap and collapse the geometry. The second, local level is linked to the global structure, with a higher control point resolution. These control points have freedom of movement in x, y, z dimensions, but without the ability to overlap or spatially ‘dissolve’ the folded logic of ‘hill’ and ‘valley’ points defining a folded geometry’s structural integrity as exemplified by the origami organisation. Through this organisation, the local level subsequently consists of a series of triangular reflective elements, which can be set to one of three states, each representing a different material sound absorption property by its different absorption coefficients. The materials used are plywood with an absorption coefficient of 0.1 at 500 Hz and foam with an absorption coefficient of 0.9 at 500 Hz. The materials are combined in the manner of a sandwich, with foam in the middle and plywood on both sides encapsulating the foam. The cross section of the material makeup has a

Computationally generated and CNC milled patterned acoustic absorption composite surfaces. The variation creates an extended visual, tactile and audible sensation of the structure. Photo by Isak Worre Foged.

structural thickness of 43mm. By combining the materials, high structural stability is created across the triangular plates, with the important ability to change absorption coefficients by perforating the sound-reflecting inner surface of the space.

Environmental Simulation Model

Different architectural acoustic equations exist, with the simplest being the Sabine equation applied in the previous study, calculating the reverberation time RT60, that is, the time it takes sound to diminish from 60 dB. From this the Millington-Sette equation is developed; most importantly for this study, the Eyring [Eq. 8.1] equation is developed from these two equations. This approach offers a higher resolution of the evaluated space, as material definition is established to a more detailed degree than in the former two equations (Long 2014). Particularly important is the ability of the Eyring equation to separate different material parts and their geometry, working with heterogeneous materials and geometrical assemblies of elements. The Eyring equation for architectural acoustics (RT = reverberation time, V = volume, S_i = surface of material, α_i = absorption coefficient of surface material):

$$T_{60} = \frac{0.161V}{-S_T \ln\left[1 - \sum(S_i \alpha_i / S_T)\right]} \tag{8.1}$$

From the Eyring equation a specific acoustic simulation method is developed based upon the introduction of a 'listener plane' that is spread out horizontally within the parametric space at the height of the listeners' ears [Fig. 8.4]. The Eyring equation does not integrate specific acoustic properties at a specific point within a given space, so the study additionally integrates a ray-tracing functionality that allows evaluation of the sound perceived on the listener plane. Furthermore, this allows the tracing of the sound pressure on the listener plane by the equations [Eq. 8.2 and 8.3](Lp = sound pressure, r1 = distance from sound source, r2 = another distance from sound source, L1 = sound pressure at r1, L2 = sound pressure at r2).

$$L_p = 20 \log_{10}\left(\frac{p_{rms}}{p_0}\right) \tag{8.2}$$

$$L_{p2} = L_{p1} + 20 \log_{10}\left(\frac{r_1}{r_2}\right) \tag{8.3}$$

Reverberation time and sound pressure level combined serve as the acoustic simulation of the intended design space.

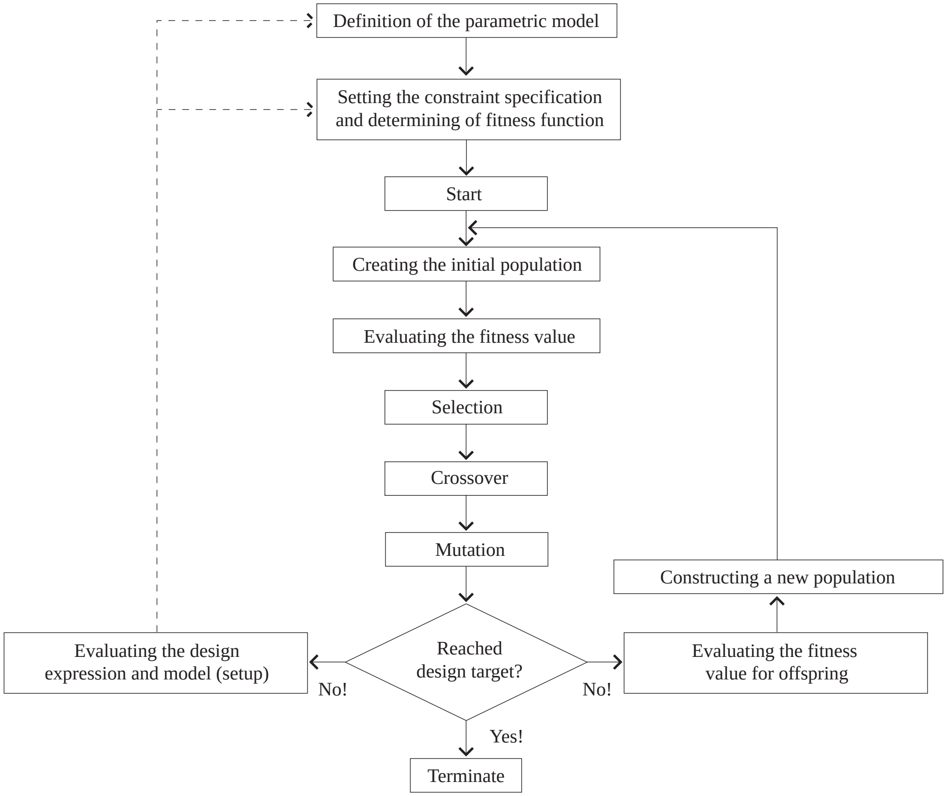


Figure 8.3

Diagram of the evolutionary design process by Isak Worre Foged.

Evolutionary Model

An evolutionary algorithm is utilised to gradually develop the acoustically based architecture. The algorithm progressively seeks to improve the design (phenotype) based upon its genotypic mechanisms of selection, crossover and mutation functions [Fig. 8.3]. The theoretical background for evolutionary algorithms has previously been discussed. What is particular to this study is the formulation of a multi-objective fitness function based on a 'preference-based-weighted-sum' search description. Several different methods for multi-objective search procedures are available, with most using a Pareto-optimisation procedure ranking solutions on a Pareto front through, for instance, a 'dominance-based' selection procedure, as is the case on the SPEA2 algorithms (Deb 2009). Such processes allow an equal distribution of potential candidates and the finding of the best candidates in all search fields (ibid.). The objective here, however, is to formulate a search process in which design influence is embedded into the search procedure, thereby effectively changing the search criteria on the basis of design intentions. By this approach, a concatenated search function can be formulated, including weights that can be modified by the designer as part of the search for different solutions for a sound-based architecture. Furthermore, a fast Standard Genetic Algorithm (SGA) can be applied (Rutten 2013), using the same open solver as within the previous study.

Following the objective of the study to develop and examine an approach that enables a more explicit relationship between musicians, structure and listeners, it was decided to search two contradicting architectural acoustic properties within the same space [Fig. 8.4]. By having a position 'beta' at one 'end' of the parametrically defined space aiming for a short reverberation time, approximately 0.9 seconds (good for speech), and a position 'alpha' at the other 'end' of the space that aims for a long reverberation time, approximately 1.4 seconds (good for classical music), the two search processes for each 'end' would logically neutralise each other within the fitness function. However, by integrating the acoustic assessment from the simulation method described above in both positions and inserted into the equation below [Eq. 8.4], a singular search process can be initiated.

$$f(x) = \beta + m \cdot \alpha \tag{8.4}$$

When the reverberation time alpha increases within the fitness function, it actually decreases in its acoustic properties. The variables that are altered in the genetic algorithm are the x, y, z coordinates of the global and local geometric setup described above and the additional application of the three material properties on the inside of the structure. The fitness function thus describes the material absorption coefficient as a variable, which influences the sound sensation of the space. As mentioned, two materials are chosen, wood and foam, which have very different absorption properties, wood 0.1 and foam 0.9, at 500 Hz. Additionally, a 'mix' of the two materials is made by having a surface created partly from wood and partly from foam. This causes the search space to move from three dimensions to six dimensions because of the three different material properties added to the x, y, z dimensions.

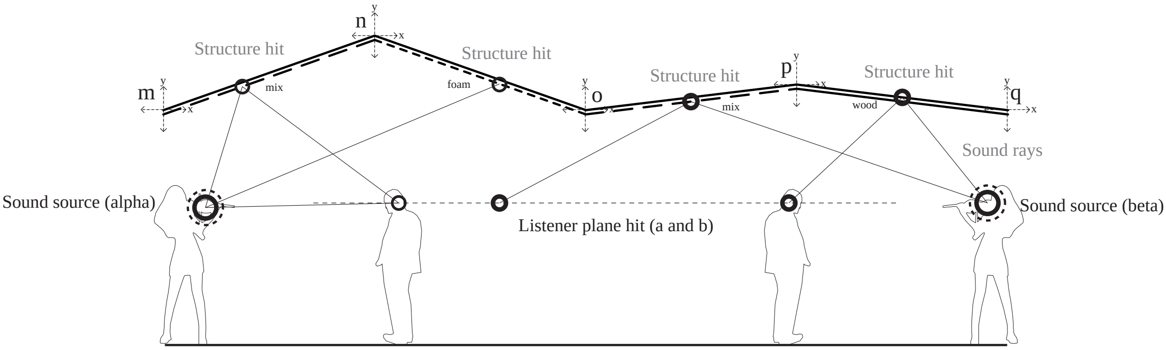


Figure 8.4.

Diagram of a simplified geometric model for a multi-objective fitness function towards a reciprocal acoustic relationship between musician, architecture and listener. Diagram by Isak Worre Foged.

8.2 Design experimentation

The combined methods above are then applied as an architectural design methodology, similar to the previous study in chapter 7. However, by extending the search space from three to six dimensions, by a more profound material integration, the search field is greatly expanded. Taking what was learnt from the previous study, the evolutionary design model is divided into two segregated modes enabled by the definition of the parametric model. The two approaches are intended to:

(1) Search volume and materialisation by evolutionary processes with all variables activated

(2) Search volume and materialisation by evolutionary processes with successive variables activated.

Within (2) the design method first applies a search with the objective of generating the global and local forms, and secondly generates material organisation of the elements, selecting between the three absorption states, which subsequently create the milling pattern that perforates the elements. Studies are done by allowing the progressive combined model, as based on the three models described above, in successive runs to explore the capacities to search for multi-objective sound-based environmental constructions. The evolutionary search model and its variables are defined by:

$$Acoustic\ Tectonics\ 2\begin{cases} Minimise & f(x,y,z,m) = RT \\ subject\ to & -10 \leq x,y,z \leq 10 \\ & 0 \leq m \leq 2 \\ Mutationrate & 0.2 \\ Population\ size & 100 \end{cases}$$

In contrast to the previous study, the applications of the methods and combined model are studied by a single sound source emitting towards a listener plane defined by the boundaries of the enveloping structure.

8.3 Results

The study illustrates an approach to the articulation of sound-based environmental constructions through evolutionary search processes. Similar to the previous study, the parametric model is based on elements that, as a whole, undergo formations when environmental agency is applied to the model. In contrast to the previous study, each element has the ability to transform its respective material properties by its absorption coefficient in addition to its reflective properties based on the angling of the sound rays.

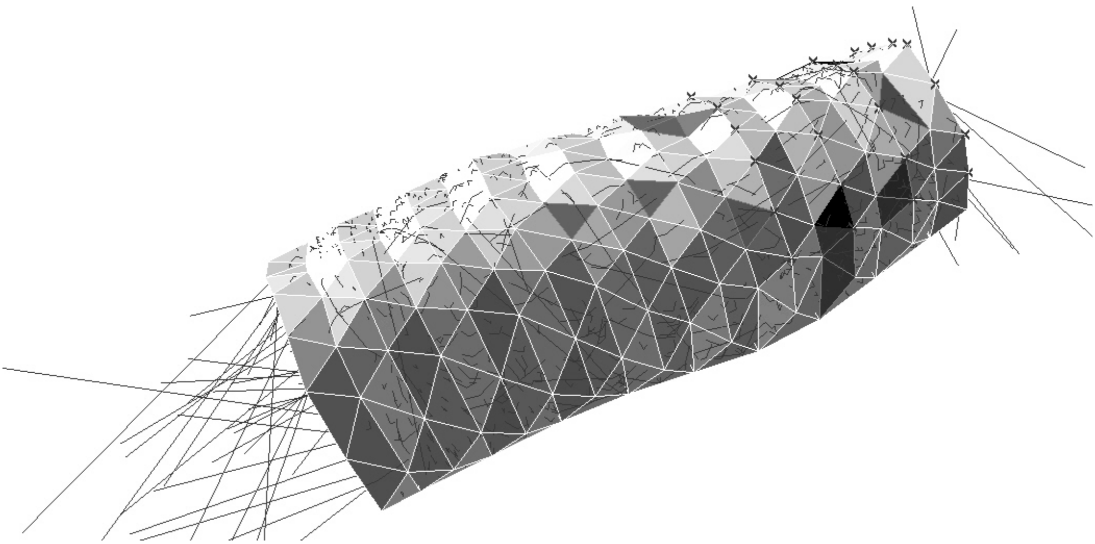


Figure 8.5.

Computational model based on a parametric model, an evolutionary model and an acoustic simulation model. The figure illustrates the geometry, three types of materials by shades of grey and the ray-tracing analysis. Screenshot of compuattional model by Isak Wore Foged.

Specifically, the study finds that:

(1) The developed method and the following experiments through a combination of evolutionary computation and acoustic simulation can be used as a strategy to evolve a sound-oriented instrumental architecture based on volumetric and solid matter organisation.

Hence, evolutionary processes can be applied as an operational approach to multi-objective search procedures for an advanced method of specifying perceived sensations for humans. This is evident on the chart [Fig. 8.7] illustrating how the computed evolution of sound properties from the two positions, alpha and beta, develop within the pavilion space on the listener plane. The y-axis of the graph has reverberation time values from 0-1.4, and the x-axis of the graph has iteration time values from 0-1000. The reverberation time evolution chart is based on a search for maximum RT60 in alpha and minimum RT60 in beta to test the acoustic boundary performance of the space. The computed results stabilise at alpha =1.4 and beta = 0.2 after 700 iterations. Thus, from an initial starting point of almost equal RT60 in both positions, the approach clearly modifies the organisation of reflective geometry and material distribution, causing a multi-objective sound space to be gradually evolved.

(2) If design time is an aspect of concern, as it is in conceptual design phases, the method can be divided into two successive steps by first organising the space structure and then organising the material application.

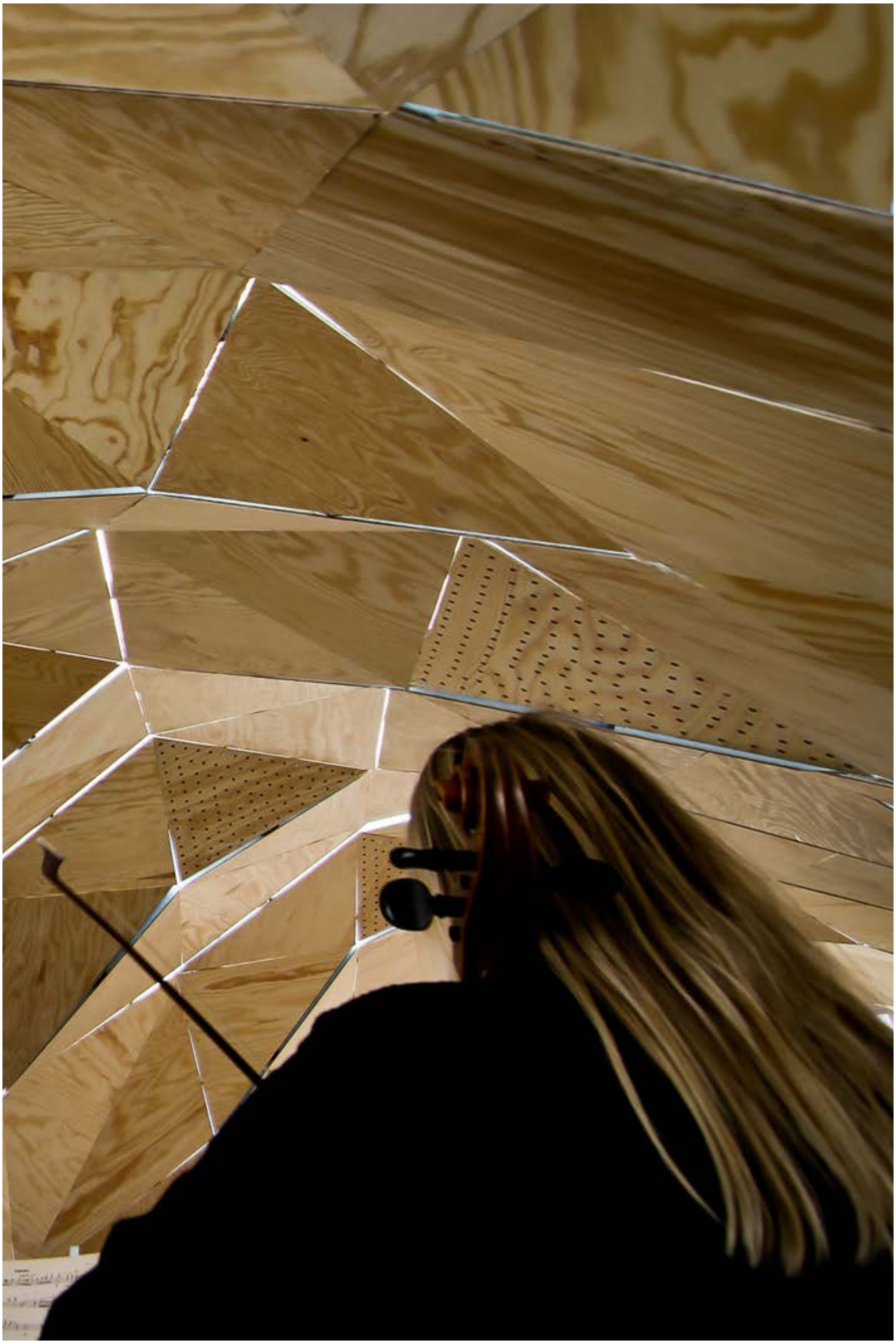
This, obviously, reduces the six-dimensional search space into two runs of three dimensions. However, this may serve to clarify the effect of the evolutionary procedure in relation to each set of variables (spatial and solid material). In contrast, such an approach may also reduce the potential of finding a solution in the six-dimensional solution space due to a lack of combinations between the extended solution set of six dimensions.

Based on post-play questions about the musicians' perceived acoustic experience, the musicians found that the structure enhanced the reverberation time and thus extended the instrumental capacities of the non-amplified classical instruments. A musician positioned in the low-reverberation end of the space noted that the sound was clear, but without enough reverberation time. This can be interpreted as negative, even though in this particular case it is actually positive, in the sense that the musicians were, without knowing it, placed in the low-reverberation end of the space.

8.4 Conclusions

The study goes a step further than the study detailed in the previous chapter. Focus within this design experiment was placed on the extended material dimensions as applied to the evolutionary procedure. In common with the earlier study, the methods, model and experimental probe are evaluated against the four causes as a measure of the Environmental Tectonic properties within this specific study.

Full scale architectural research probe created from the experimental studies. The reflective surface and the surface absorption by milling processes form the acoustic environment for classic music. Photo by Isak Worre Foged.



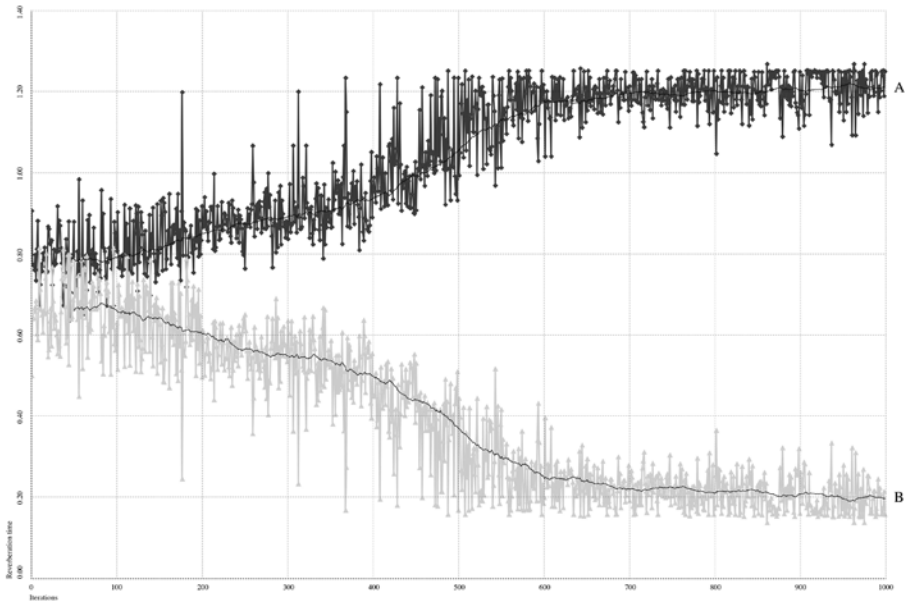


Figure 8.7

Computed evolutionary progression as understood by the progression of reverberation times for the two instrumental positions within the structure. Graph by Isak Worre Foged.

The progressive form development through the evolutionary process, causa formalis, is considered more readable here than in the previous study. This statement is based on the ability to read the appearance of two opposing conditions simultaneously, which enables a more clear distinction between the initial form and the developed form, based on the immediate comparison between the two opposing acoustic properties. The materialisation is similar to the form, developed through the gradual process of changing the surface structure by milling, of a composite materialisation of foam, wood and sound. This effectively alters the relation between the sound, the architecture and the listener, thereby advancing the impact of the material causality in relation to the objective of the study. Causa materialis is in turn reaching a higher articulation in comparison to the previous study. The final form, causa finalis, is the last step of the evolutionary process. The final form is intrinsically based on the sound environment and the organisation of elements that, by their individual materialisation and interlocked triangular system, construct the perception of a global formation system with local differentiation. The effect, causa efficiens, is primarily twofold in the audible and visual impact on the listener. By the spatial positioning of the musician and the listener, the effect of the form is further articulated. As music is dynamically perceived and the sound sources may be dynamically positioned as an architectural musical instrumentality, the study illustrates a method for constructing temporal and dynamic environmental effects in a visually static construction.

8.5 Discussion

With regard to the setup for the research study, a small architectural space was preferred due to the possibilities of creating a 1:1 demonstrator with a subsequent performance by musicians with an audience. A first issue arises in the capacity of creating long reverberation times in very small spaces, as the sound will need to bounce several times to extend the audible period to a level desirable for classical music. Due to fabrication issues (fabrication accessibility and on-site modifications to a geometry with no margin of error), wood was chosen as the outer element in the sandwich structure and therefore the reflective surface. Other materials with smaller absorption coefficients could potentially improve the material capacity within the study, which would allow for greater abilities to differentiate between low and high reverberation times for different positions. The acoustic analysis takes into account an audience-filled space. This aspect could be developed to allow for an empty, partially occupied or filled space, which would directly affect the absorption of the rays bouncing off the floor area. However, the space was filled during the performances and therefore the difference between the studies and the realised space was minimal. Nevertheless, one musician noted, somewhat humorously, that the reverberation time would be further prolonged and improved if no audience were present, allowing the sound to bounce off the concrete floor area.

Figure 8.8

Full-scale demonstrator as probe of acoustic tectonics at the Aalborg harbour front (2012). Photo by Isak Worre Foged.

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9

Thermal Tectonics I

In a different way than in the past, man will have to return to the idea that his existence is a free gift of the sun.

(Georgescu-Roegen, 1971)

9.0 Preliminary

In the section Energy, within chapter 3, Environments, examples and suggestions were raised on how to form an environmental architecture from the local exergetic capacities, the available energy that can do work in an environment. In this way, the overall form of a building describes not only its architectural language, but also its capacity to become environmentally sustainable in relation to its local solar climatic environment. Movement of the sun in relation to the Earth, its surface orientation and its mass constitute the weather conditions locally and globally as it regulates air flow, heat accumulation, heat transfer, et cetera (Oke 1987). These relationships, solar geometry and mass, form the microclimatic environment for life and its rhythms. The solar environment is thus the singular most important factor in relation to climatic environmental architecture. The creation of architectural building forms as derivatives of the solar environment thus has the potential to improve the context-specific reception and containment of energy towards environmentally sustainable architecture. If the position of the sun in relation to the Earth's surface orientation and its matter properties can determine local environments, as briefly described above, then that same capacity could also be activated as a strategy for the generation of environmentally sustainable architectural forms and their matter properties. The discussion within the thesis Introduction (chapter 1) and Environments (chapter 3) together with capacity that form and distribution of matter have to lower the energy used in a building by up to 80% (Petersen 2011) motivates this specific study.

The background on previous solutions is a recent tendency in environmentally sustainable buildings, particularly in northern climates, to design buildings to minimise surface to volume relations, as seen in the *Green Lighthouse* project [Fig. 9.1] from 2009 designed by Christensen & Co Architects (Edwards & Naboni 2013:216). It uses its circular planar form as a form of environmentally sustainable geometry. While it is currently an advanced example of the sustainable architectural form in the built environment, the design of architectural forms remains largely based on design principles, rather than computational form-finding methods. The *Greater London Assembly* designed in 2002 by Foster and Partners is another project organising the building geometry in relation to the solar climatic environment. Here, the architects pair a parametric model with the analysis of solar inclination and window shielding to decrease glare and unintended exposure (Whitehead 2003).

A progressive additive construction model based on a uniquely developed generative algorithm is the intended background for new solutions. Generative algorithms, as described in Computation (chapter 5) can be devised through different techniques geared towards the articulation of architecture (Riiber 2013). Such algorithmic techniques in the simulation and generation of architectural form have evolved rapidly over the last decade, enabling the handling of complex climatic, geometrical and manufacturing aspects. The ability to construct advanced generative formal organisations has been shown in works by architects Marc Fornes and Roland Snooks (Leach 2009) through fractal systems and swarm systems. Other advanced algorithms for the generation of forms in architecture and related fields are created in the work of Alisa Andrasek (Andrasek 2006) and Jenny Sabin (Sabin & Jones 2008).

Figure 9.1

The 'Green Lighthouse' (Copenhagen University) by Christensen & Co. Architects (2009). The circular building form as an approach to energy-based architectural design. Photo by Isak Worre Foged.

It is attempted in this study to create a generative algorithm that, through additive processes, constructs building forms that are based on the solar climatic environment. The potential is to increase the exergetic capacity of the building for further possibilities of articulating the thermal environment directly perceived by humans. By this process, it is attempted to reveal the relationship between the environmental influence of the sun and the additive construction process.

The study presents a generative method and a model based on a developed generative rewriting algorithm, which explicitly connects the generated building forms to the climatic environment based on solar-earth-matter relations. Specifically, the presented study investigates the capacity to create environmentally sustainable architectural forms that are a response to a process of encoding a six-dimensional factor space, constructed from polar coordinates, time, material properties and solar climate. It does so by the application of matter properties to digital construction elements, which by successive application constructs building formations.

9.1 Methods and Models

The study applies a series of computational methods to generate and assess the distribution of elements into a solar energy-based architectural formation. Computation is used to simulate solar energy and thermal storage based on established mathematical models. This is combined with a developed generative method presented below, which distributes matter in space, progressively resulting in architectural forms. The last component is the model output relationship that describes the capacity to receive, store and transfer energy in order to evaluate the generated forms in a comparative analysis with conventional building geometries. The study is created by using the open-source programming language *Processing*, developed by Casey Reas and Ben Fry.

Environmental Simulation Method

The encoded solar insolation analysis is based upon geometrical relations described in Lambert's Law (Oke 1987). Through the integration of the solar geometry, azimuth and zenith angles, the solar energy contribution can be calculated when related to the inclination of the surface receiving the solar energy. The variables of location and time can be dynamically changed within the generative model described below. The simulated surfaces of the distributed elements are always facing 'outward', as the model intends to form visually 'closed' structures. The simulation model does not calculate the intersection with obstacles, so it does not include possible shadows cast by neighbouring buildings. This aspect is excluded as to focus on the specific form articulation by the solar energy environment.

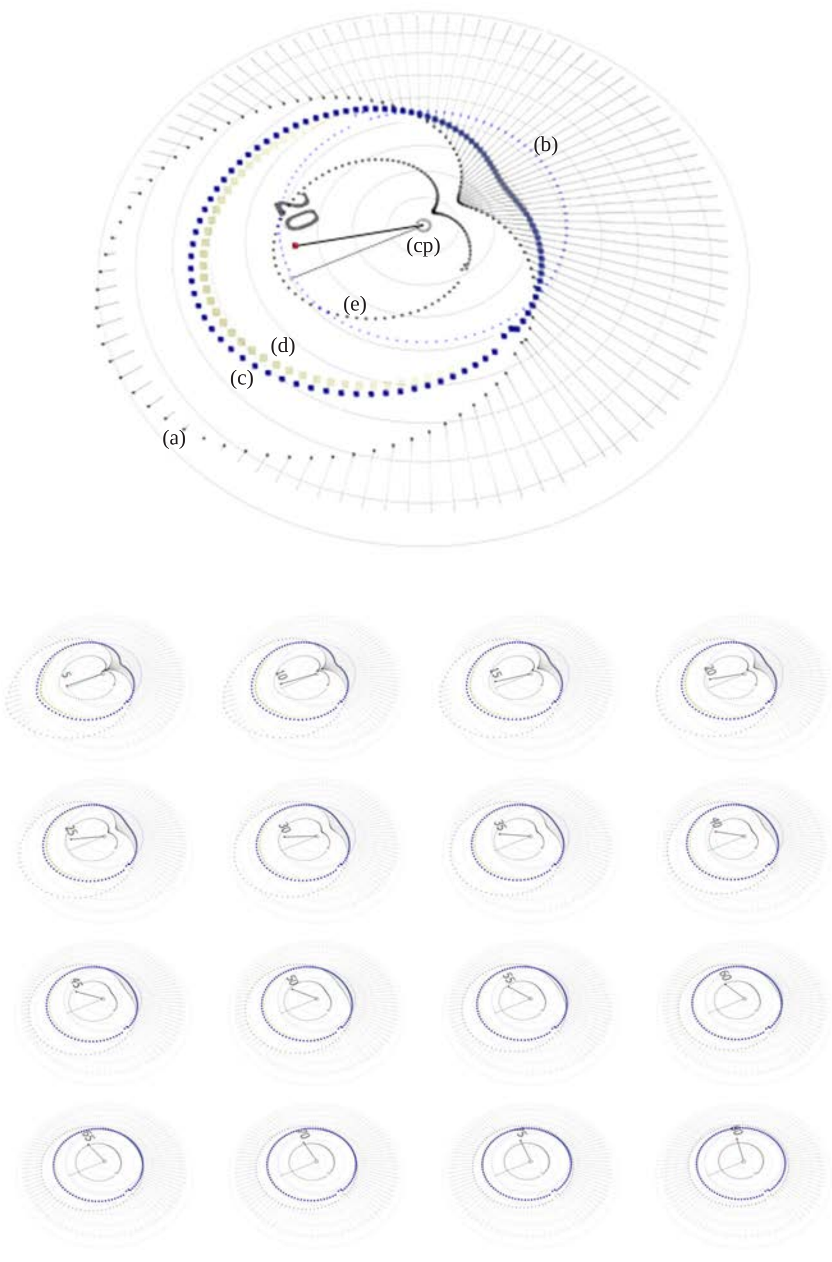

Figure 9.2

Distribution of matter in relation to energy solar energy. The formation (top) illustrates the 'ideal' form with sun vector at 20 degrees. The 16 figures at the bottom illustrate the change of form as a function of sun vector. Drawings by Isak Worre Foged.

Generative and Parametric Model 1

With the intention of using the exergetic capacity of solar energy, thermal forms are based upon the combined aspects of receiving, containing and transferring energy. Receiving energy requires an extended surface facing towards the energy source, following Lambert's Law. Containment in architecture is based upon minimum transfer of energy from the inside to the outside, thereby minimising the surface to volume ratio. Transfer of energy is related to the ability to move the energy received at the external surface to the centre of the structure. Based on these factors, an algorithm can be described that is based on the principal logic of 'the more energy received on a surface of an element, the farther from the core the element can be positioned' [Fig. 9.2]. The principle initiates the generative procedure, with the following element created based on the same evaluation but moved by being rotated around a central point to position it next to the previous element. Instead of describing the distribution of elements by using Cartesian coordinates, the model uses Polar coordinates, allowing a simple rewriting procedure in which the angular position is computed, with the radius at the centre of the form defined by the irradiance calculated. From this, it follows that the farther the elements are positioned away from the centre point (cp), the greater the distance is between the elements, effectively extending the combined surface oriented towards the energy source. The progressive additive process creates the formation of the elements (a). Following the same procedure, but with a fixed distance between (cp) and a created element, a circular form with optimum surface volume relation is created. This process creates the elements (b). The following generated formation is based on a weighted distance between the elements (a) and (b), denoted elements (c). The weights determining the approximation to (a) or (b) can be parametrically set by the designer and serve as an equilibrated formation between an 'optimal' energy-receiving form and an 'optimal' energy-containing form. In the studies performed in this chapter, (c) is always half the distance between (a) and (b). From (c) matter is positioned according to the description below.

Generative and Parametric Model 2

Following the additive generation of form, matter properties are applied to the generative model [Fig. 9.3] through three different aspects: (1) u-value, the heat transition coefficient, (2) g-value, the solar gain coefficient, and (3) thermal mass. These are selected based on their direct reference to established architectural terminology, and from a sensitivity analysis of the most influential passive factors for environmentally sustainable architecture (Petersen 2011; Winther 2013). The factors are plotted into a scheme [Fig. 9.4] in relation to the solar energy aspect above. The scheme is related to the northern hemisphere, in which southern orientations are affected by higher solar gain. The scheme could be reconfigured for other locations and paired with the above form-creation algorithm, generating results other than those presented below. Merging the generative model with the matter aspects described above into one model, the following algorithmic procedure is defined:

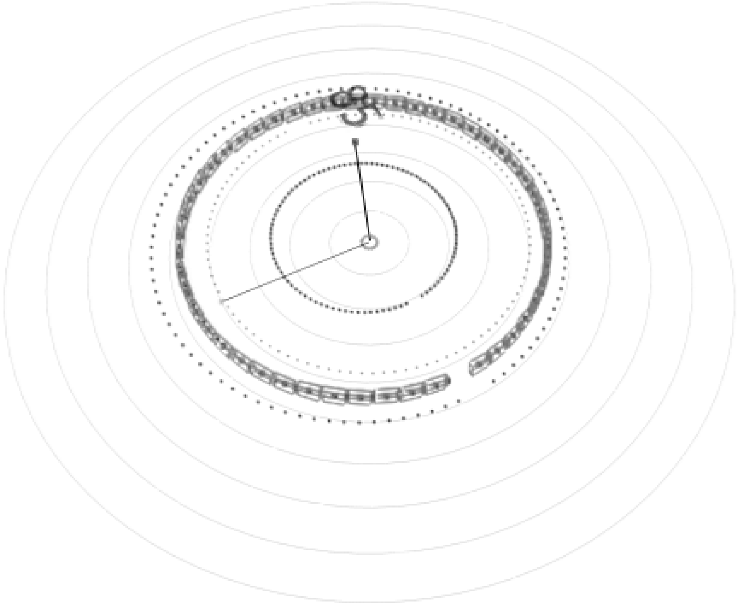

Figure 9.3

Generative Model 2 distributes material, such as bricks based on its thermal capacities, on the equilibriated curve between the receiving form and the containing form. Drawing by Isak Worre Foged.

```
Distribute test elements uniformly around centre point (cp)
for i < 360 && n < Iterations, do
    Calculate element angle vector from centre to distributed element
    Calculate sun vector
    Calculate angle between element (a) vector and sun vector
    Calculate radiation energy on each element
    Distribute elements from centre based on quantity of solar energy
    Distribute element (b) from centre with same radii, creating uniform
    circle
    Calculate distance between elements (a) and elements (b)
    Distribute elements (c) between elements (a) and elements (b)
    Calculate angle between element (c) and sun vector
    Calculate radiation energy on each element
    Calculate "optimum" g− and u−value materials
    Distribute elements (d) and scale/colour elements from calculated g−
    and u−values
    Calculate stored energy in elements (d) based on material property and
    received energy
    Calculate radiant energy emitted from energy stored in elements (d)
    Distribute elements (e) towards centre based on radiant energy
    if Exit condition test = True then
        Exit Generate
    else if Exit condition test = False then
        Elements (a,b,c,d,e) angle > TWO_PI move elements (a,b,c,d,e)
        distance(z)
        Return to 1:
    end if
end for
```

9.2 Design Experimentation

The following three experimental design studies [Fig. 9.5] are conducted based on the developed algorithmic procedure as laid out above.

The first study is based on calculating the 'optimum' application of u- and g-values positioned on the elements located by the distribution algorithm (generative algorithm 1). The algorithm (generative algorithm 2) then positions matter characteristics, rather than known building materials, such as bricks, concrete or wood. The distribution of the values of the elements is based on the graph [Fig 9.4]. This is done with the intention of suggesting a distribution of matter and its properties among environmental constructs based solely on their thermal properties.

The second study is based on the thermal properties of bricks (solid matter in geometric entities) and applied to the calculations of thermal storage distribution (generative algorithm 2). This affects the procedure of distributing thermal material by locally scaling the elements. This in turn influences the accumulation of thermal

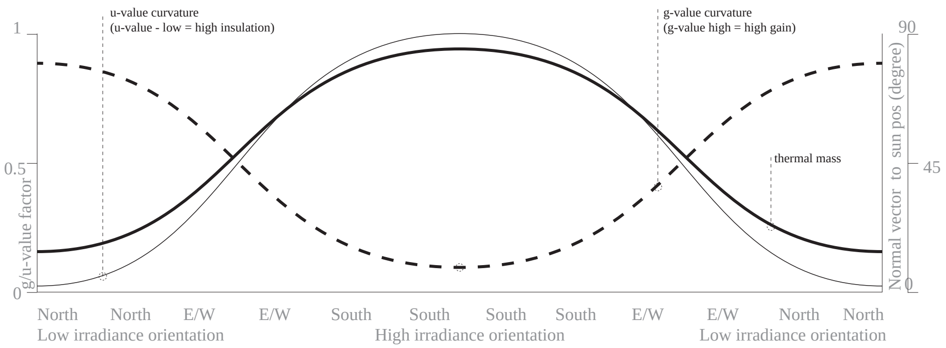

Figure 9.4

Diagram of the relationship between environmental conditions and the distribution of matter. The graph values are encoded into the model for the Northern Hemisphere. Diagram by Isak Worre Foged.

energy for further distribution of radiation on the inner side of the form. This process intends to apply material for thermal storage only where it is needed.

The third study evaluates the solar energy on an element's surface and, based on the evaluation, suggests two material properties, high- or low-energy absorption, for application to the specific element. This approach has the intention of making the computational method, together with the local environment, 'choose' a material from a small catalogue of available materials that can be defined prior to the generative process by the designer.

9.3 Results

In order to understand the exergy-related capacities of the forms generated, a comparative analysis is done between conventional building forms and the forms derived from the method and algorithm. A comparison is provided of eight simple aspects to determine the ability to advance the generation of building forms towards an Environmental Tectonic approach. The comparative evaluation is based on the relationship in building forms between receiving, using, storing and transferring energy by, for example, calculating the ratios of solar exposed surface area to floor area [Fig. 9.6].

Specifically, the study finds that:

(1) Thermal energy-based architectural forms are non-circular.

(2) Thermal energy-oriented buildings can advance the global building geometry and local distribution of matter by the developed method and model.

The formations created by the developed method and algorithmic model show that an 'optimal' building form based on the solar environment is seldom circular. The circular form is only desirable when the solar beam is located perpendicular to the Earth's surface, or when the intent is to focus solely on containing energy. For other solar environments, based on exergetic processes, a building form based on the combination of containing and receiving solar energy is more effective. This is clear from the relationship shown in the different building typologies [Fig. 9.2]. If a building context that included solar shading obstacles were to be integrated, the above statement would be even more distinctive, as the solar irradiance would be increasingly different from the ideal unobstructed one calculated by the path of the sun represented by the solar vector. In climates with a lower sun angle, the form equilibrates into curvilinear forms with an extended surface towards the source and decreased surface in the opposing direction. This is particularly evident when observing the forms [Fig. 9.6] where the solar vector lowered to six degrees results in novel irradiance-based building forms.

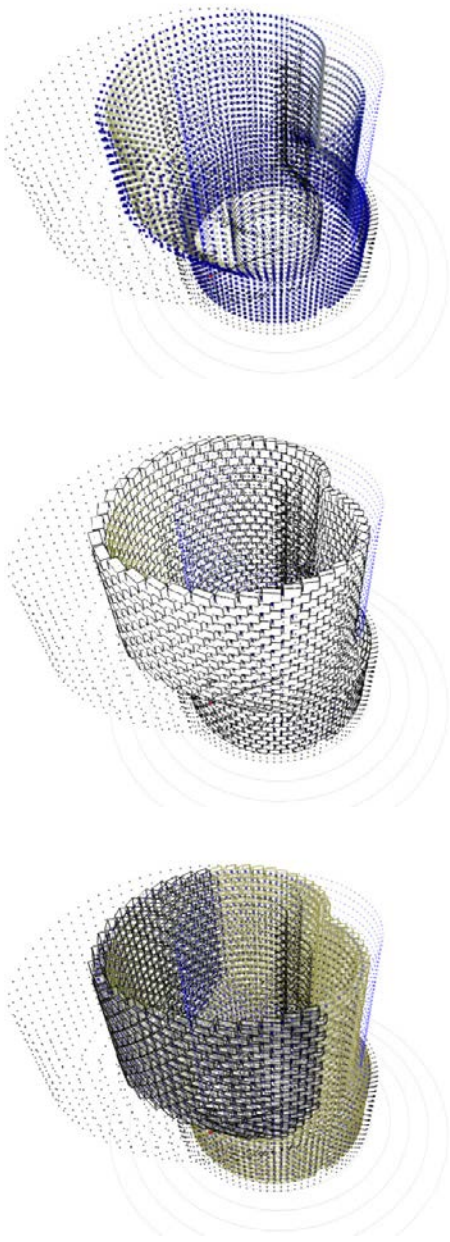

Figure 9.5

Three output geometries and matter organisation by the combined model of algorithms from generative models 1 and 2. Top figure is the distribution of matter properties. Centre figure illustrates the distribution and scaling of clay bricks. Bottom figure illustrates the distribution of solid matter types in brick format according to solar environment. Drawings by Isak Worre Foged.

9.4 Conclusions

The study is based on a developed generative algorithm that has illustrated how a simple recursive rewriting procedure can construct climatic environmentally based architectural forms. The four causes are used to evaluate the computational probe as an approach for Environmental Tectonics.

In contrast to the previous studies, in chapters 7 and 8, from a form-development perspective, the study has shown how an architectural form can progress from 'nothing'. The axiom for the procedural method is the positioning of an element and its matter properties based on information from the solar environment. The algorithm functions similarly to fractal organisations, as elaborated in Computation (chapter 5), but differs by rewriting from the same spatial location, rather from the end position of the latest element created, as is the case in L-Systems. The cause of its formation, causa formalis, is explicitly readable in its conception. Being based on the solar vector, the scale of the building form is adjustable without losing its properties, as the angular relationship between the Earth and the sun alters minimally when considering the scale of buildings. This, however, may reduce the clarity of the building scale when generating the building form. The study explores a possible new method for materialisation in architecture by the distribution of matter qualities, such as thermal storage properties and thermal transmission properties, rather than the application of known building materials. This is suggested to emphasise the materials' capacities to act environmentally and promotes the distribution of matter by environmental intentions, causa materialis, rather than by the application of visual expressions alone. The cause of the final form, causa finalis, is directly derived from the intention to orient the building in respect to the solar environment. The form then follows the aforementioned statement by Darcy W. Thompson positing that *'the form of an object is a diagramme of forces'* (Thompson 1992). In the case of this study, the generated forms are derived from a singular force, giving the explicit relation to the environment. The effect of the probe, causa efficiens, as an environmentally oriented architecture perceived by the human may be less obvious. While the prior studies showed a direct relationship between an Environmental Tectonic probe and the sensing human, from which the extended aesthetic dimension is created, the probe within this study operates on a scale that does not offer evidence of an immediate relationship to the sensing human. Hence, the architectural form and its materialisation are oriented towards an energy-optimising architecture, rather than the intended human-oriented environmental sustainable architecture as formulated in part two of this thesis.

9.5 Discussion

While a rich architectural legacy on advanced structures has been defined by, among others, Frei Otto (Otto & Rasch 1996) *'towards an architecture of the minimal'*, the study illustrates an application of the proposition of 'maximum structures' as presented in chapter 4, Tectonics. The generative model shows this by distributing material properties, such as thermal mass, solar gain properties and heat transmission

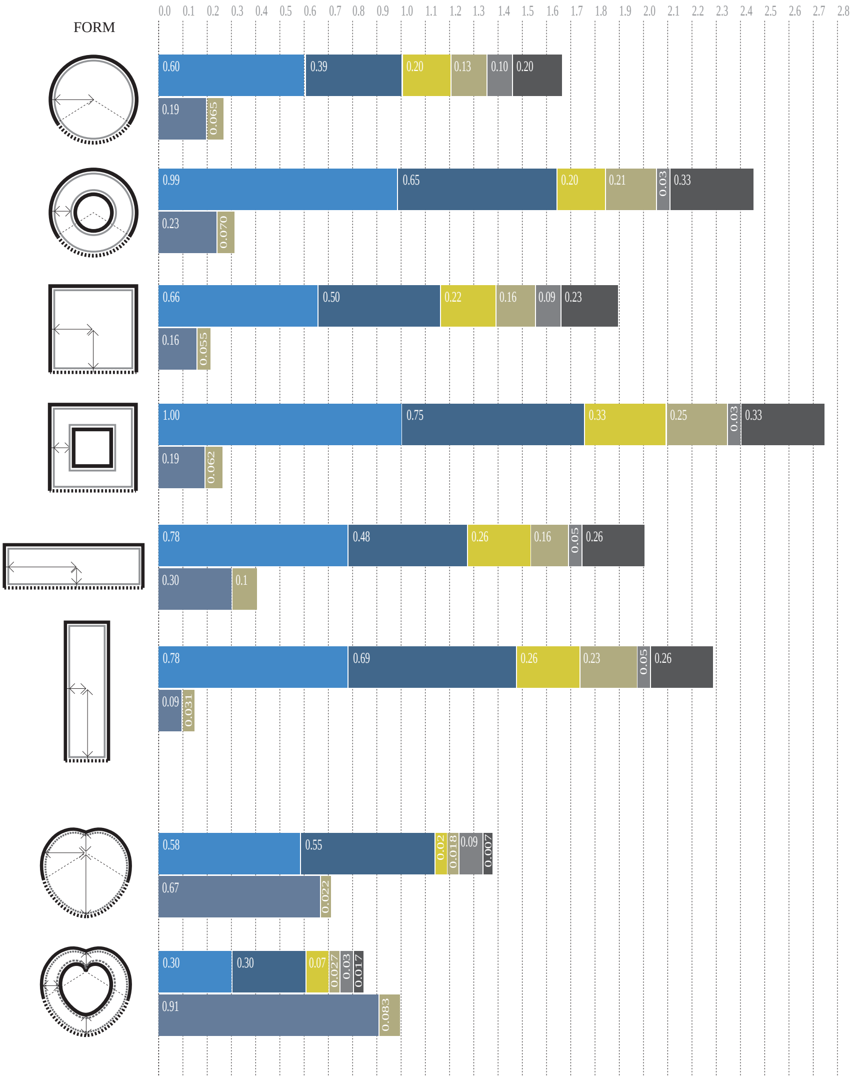

Figure 9.6:

Diagram of forms and their relation to computed factors of energy. The values are aggregated in the scheme to illustrate the combined measure when adding the different relations presented in the legend together. Diagram by Isak Worre Foged.

properties, for a partial heavy and composite matter organisation. The suggestion here is not to divert from 'minimum structures', but rather to consider more integrative 'maximum structures' as a concept for environmentally sustainable architecture as well.

The study is based on solar environment-based forms, but as the predominantly built environment changes through urban reconstruction over time, the local climatic environments alter with it in a reciprocal manner. This suggests that the approach could be expanded into organising matter with responsive properties to accommodate modification to the local thermal environment. This would require that a simulation of the human-perceived thermal environment be integrated into the generative model or incorporated through a subsequent articulation of the envelope on a human scale.

Surface[m2] / Floor area [m2]
E.Surface[m2] / Floor area [m2]
LE.Surface[m2] / Floor area [m2]

Surface[m2] / Volume [m3]
E.Surface[m2] / Volume [m3]
LE.Surface[m2] / Volume [m3]

Surface - Core [m]
SurfaceVolume[m3] / Volume [m3]

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10

Thermal Tectonics II

Thermally active surfaces stand to advance architecture's practices and performances: its techniques, technologies, professional and ecological sustainability, budgets, and formal possibilities.

(Moe, 2010)

10.0 Preliminary

In the previous study, it was shown how a progressive generative algorithm could create environmentally sustainable constructions based on the solar environment. However, it was also discussed that the study related less to the direct making and perception of environments by humans due to the building scale of the experiment. This study investigates, in turn, a smaller part of an envelope. As a successor to the previous study, it applies bricks as elements, with the formation capacities stated in the chapter entitled Tectonics. Also, it can be observed that in many regions of the world, heavy and solid material is used as the primary constructive element, as it is taken and moulded from local sources. Furthermore, it has a natural capacity to respond to diurnal weather deviations in its substance by energy accumulate-and-release behaviour, thereby reducing thermal peaks by incorporating factors of thermal radiation and humidity. This natural use of material in relation to environment, availability and climate has enabled its long history of development. In particular, brickwork has the advantage of the very manoeuvrable element size that can be held in one hand as the other hand secures another brick. This size, proportional to the human creator, enables a creative making, as the elements can be organised in numerous formations. From above, the brick has sustainable (thermal mass and long lasting), structural (load bearing compression unit) and expressive (colour, grain, patina) capacities operational to the designer.

The background on previously applied solutions and research studies has focused on the structural and expressive aspects derived from organising brick assemblies. In the work of architect and engineer Eladio Dieste, tremendous spans are created through undulating and curved brick surfaces (Anderson 2004). More recently, and following Dieste's work, architect and researcher Defne Sunguroglu Hensel (Sunguroglu Hensel & Bover, 2013) is pursuing new brick assemblies through catenary systems in digital and physical studies. Brickwork as an expressive technique for architects has been applied in many works, such as Aarhus University, designed by C.F. Møller (Lind & Henriksen 2007) [Fig. 10.1] several works by Exner's architectural office (Jensen 2012) and the Ökumeniche Forum Hafencity by Wandel, Hoefer, Lorch + Hirsch. Currently, through the use of robotic manufacturing techniques by the aforementioned Gramazio and Kohler (Bonwetsch et al. 2007) in the Winery Gantenbein and the Venice Biennale project in 2008, other expressive and formalistic organisations are created. The advanced methods of handling brick assemblies, shown through the brick layering systems enabled by robotics, have been presented through several studies by Gramazio and Kohler (Gramazio & Kohler 2008; Gramazio & Kohler 2010; Gramazio & Kohler 2014).

The background for potential solutions is derived from the physical properties of bricks in relation to both climatic and structural aspects. Furthermore, their organisation as an additive formation has the potential to remain an important building element in the future, despite its low-tech properties in relation to contemporary development of 'smart' materials. Through the perspective of applying a local material, clay, with thermal properties, easy and configurable assembly, robustness to wear over time and tactile expressions, the organisation of brick formations could contribute to enhancing

Figure 10.1

Aarhus University (1931) by architects Kay Fisker and C.F. Møller. The brickwork illustrates a deep expressive building envelope with articulated shaded and highlighted areas forming lines and weaving pattern. Photo by Poul Ib Henriksen.

the aesthetic dimension of an environmental human-oriented architecture.

What are known are the thermal, tactile and structural properties of the brick, and what is attempted in this study is an architectural design method in which these can be addressed and investigated through evolutionary processes for a human-oriented environmental architecture. According to scientist Richard Dawkins (Sterelny 2007), the general scientific understanding of evolutionary processes in nature is that adaptive processes are non-deterministic. Nevertheless, in computational evolutionary processes, such as the genetic algorithm, a target value, often a single number, must be described to pre-establish the conditions of the search (Shiffman 2012), thus leading to a deterministic search.

The central issue touched upon in this study in relation to progressive computational models within a design method is therefore the construct of a non-deterministic design process through a search-oriented deterministic evolutionary algorithm. This is interesting, firstly, because a design method, which allows dynamic input into the fitness function during the design process, is able to illustrate the ability of a design system (matter construct) to adapt to changing human and climatic environmental factors during the design process; and, secondly, because the design progression's appearance is a direct response to the climatic environmental factors involved and the agency of the maker in influencing the developmental algorithm during search processes.

By this approach and in relation to the question posed in the chapter entitled Computation, it can be asked:

How can an instrumental method be formulated for a design process based on an evolutionary process with a dynamic target?

In assessing thermal conditioning for humans, as elaborated upon in the section Modeling Environments within the chapter Environments, both solid matter (clothing and brick) and fluid matter (humidity, air velocity and air temperatures) are determinant factors in a combined perception of human thermal sensation. The factors are not singular or disconnected, but actively influence one another in a combined perception of the local thermal environment. When matter in a fluid state affects matter in a solid state and vice versa, it can be asked:

How can solid and fluid matter be organised in relation to environmental tectonics?

These specific questions relate directly to the questions already posed in the thesis Introduction. To address the questions, this study constructs a computational progressive design model as a brick assembly, which can be understood as part of a vertical envelope. The design experiment model integrates three computational models elaborated below. The models are a thermal environmental simulation model, an evolutionary model and a parametric model embodying the brick formation. In addition, a dynamic interface is developed that enables a potential designer and experimental researcher to alter design variables during the progressive search for an human-oriented environmental brick assembly.

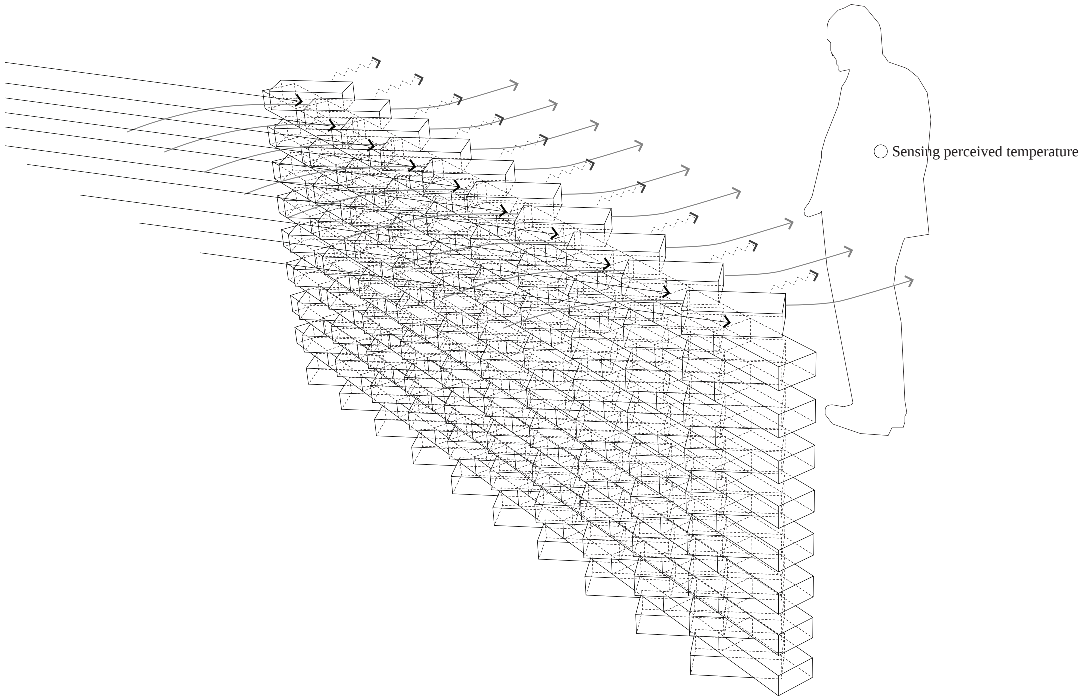


Figure 10.2

Drawing of environmental simulation aspects and the parametric brickwork model, in which each brick only has freedom of rotation over its z-axis. This effectively influences the perceived thermal environment. Drawing by Isak Worre Foged.

The study presents an idea and design method using dynamic input into a deterministic evolutionary computational method allowing the designer to modify the search target and thus approach a non-deterministic approach for environmental human-driven architectural design focused on thermal environmental aspects. It illustrates the method through the idea of organising brick assemblies, not only according to structural and expressive aspects as discussed above, but also from a thermal environmental perspective. By applying the evolutionary model developed through design experimentation, a full-scale physical probe is suggested and constructed as a demonstrator of the approach. The proposed model and demonstrator are then evaluated and discussed in relation to potential further research inquiries.

10.1 Methods and Models

As mentioned above, the presented design method developed relies on a series of architectural, computer science and natural science methods, described below. Programming of the computational model has been done in the open-source programming language *Processing*. Processing has been chosen because of its object-oriented programming structure, its implementation of time functions and the fact that it allows the construction of various graphical outputs as representations of the evolutionary process.

Parametric Model

The parametric model is based on simple brickwork bound by a half-overlay method that allows the rotation of individual bricks while maintaining them in an array, which defines the envelope surface [Fig. 10.2]. Each brick is fixed in its spatial position, with the only freedom being to move through rotation, with angular steps of 1 degree. To maintain structural integrity, a restricted rotation domain establishes load transfer from brick to brick. The domain of rotation possibilities serves as the variable that can be modified by the evolutionary search process. By the rotation of the brick, exposure to the solar vector is changed, modifying the properties for insolation. The rotation of the brick, at a specific rotation point, introduces envelope porosity, effectively changing the airflow through the envelope. Lastly, the envelope changes its visual and tactile appearance between a flat, closed surface and an open, deep surface. This, both individually and in combination, results in altered thermal properties locally at each brick and globally when considering the entire wall segment.

Evolutionary Model

The computational model [Fig. 10.3] is based on an evolutionary process that progressively improves the phenotypic articulation. In the previous studies applying evolutionary algorithms, an existing solver was used. Within this study, the solver is

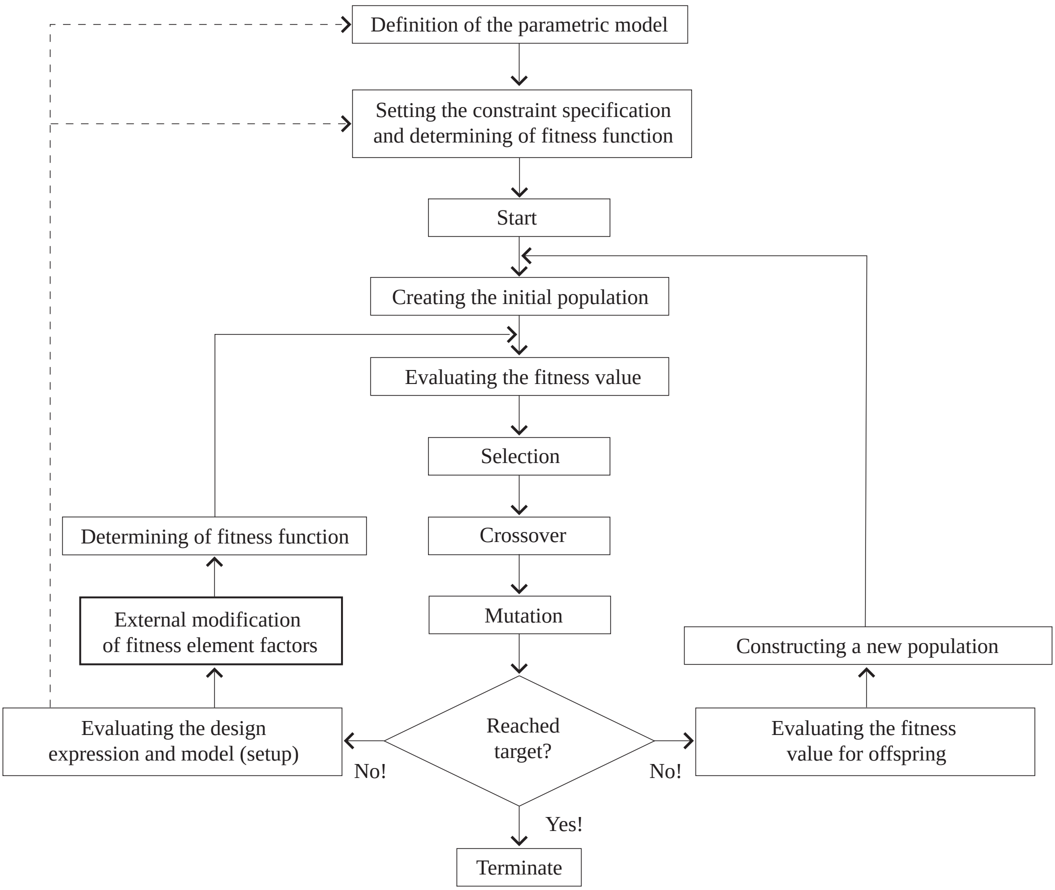


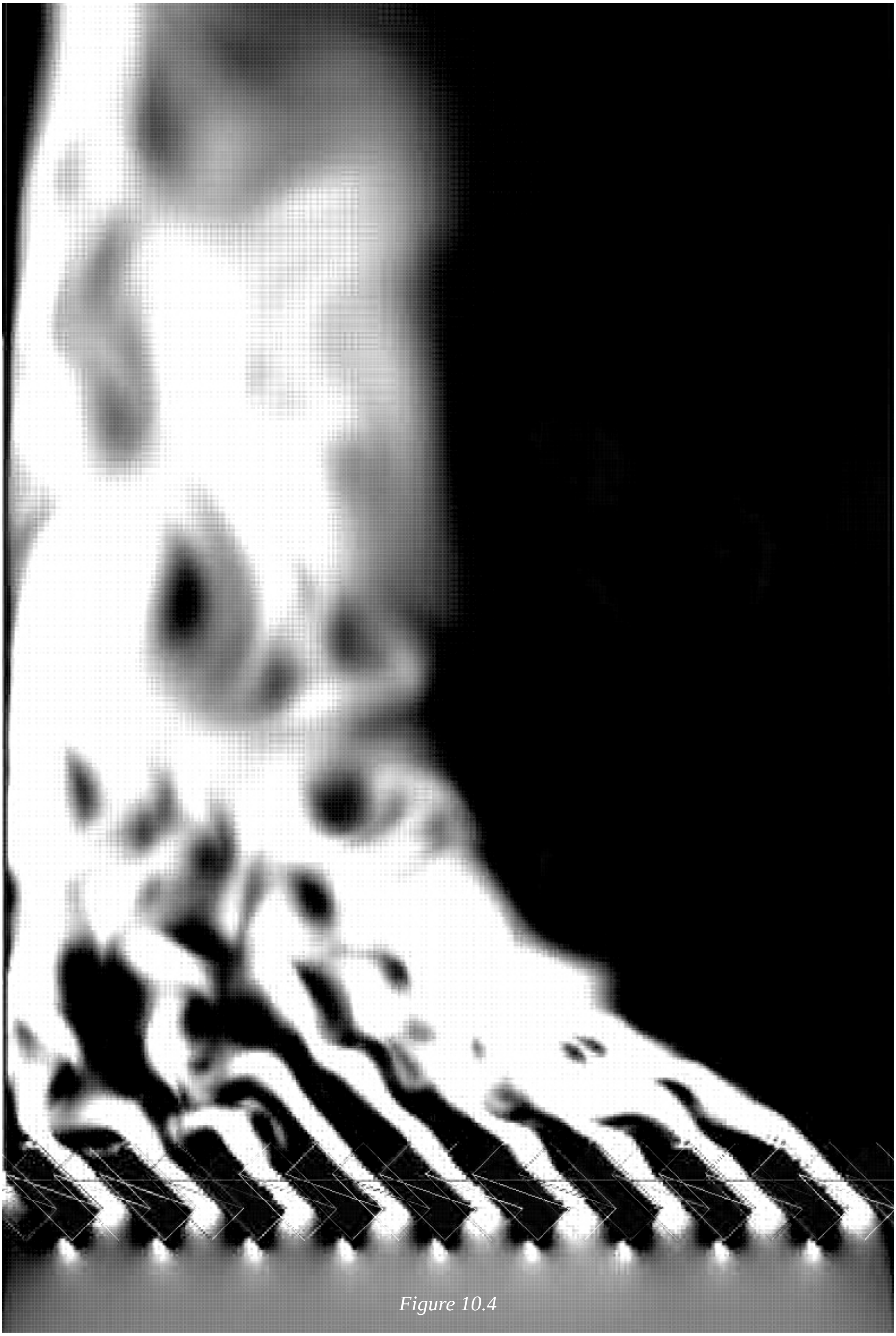
Figure 10.3

Diagram illustrating the cyclic computational process and the points of interactions by the maker. Diagram by Isak Worre Foged programmed based on the literary sources and computational methods described in the section Machine Models in the chapter Computation. As the study is based on a specified genetic algorithm, the applied computational mechanisms are described below.

Candidates are selected based on an elite selection method that takes the parts of the candidates from the top ten of the population. This method is chosen due to a relatively small set of variables, the rotation value of each brick. Reproduction between candidates is based on a random half-cut method, taking approximately half of the ‘genes’ from either candidate (parent a, parent b) to create new candidates in the next population generation. Mutation rate is kept between 1 and 2. This is based upon the relatively large population size of approximately 100. Fitness is measured according to human-perceived thermal sensation. The perceived sensation is based on Fanger’s equations for comfort temperatures, as elaborated upon in the section Modeling Environments in chapter 3 and below. The difference between computed perceived temperatures from the organisation of bricks and computed comfort temperature based on human perception related to clothing and activity describe the level of fitness, resulting in smaller differences between these temperature definitions, and therefore equalled higher fitness. The fitness score value is logarithmically proportioned in order to support the selection process. By way of extending previous work, the multiple factors and the relationship between factors involved in the Fanger equations are accessible and changeable when the algorithm search is initiated and thus act as the variables that are varied. The phenotype of the evolutionary model is described above.

Environmental Simulation Model

Danish scientist Ole Fanger (Fanger 1970; Fanger 1973) developed the comfort equations based on the understanding that human comfort relies on several aspects, both human – clothing rate and metabolic rate (physical activity) – and environmental – ambient temperature, radiant temperature, humidity and air velocity. The six factors, combined through weighted values within the equations, determine the heat balance and therefore the comfort temperature for a human being. It is clear that extended notions of effects on comfort can be mentioned, such as human acclimatisation over time or behavioural adaptation, such as movement to local warmer zones within a larger space. These considerations have been discussed in relation to Free-Running Buildings and the Adaptive Thermal Comfort model. The first aspect, acclimatisation, is omitted in this work in order to narrow the field of variables. The second, behavioural adaptation, is arguably integrated into the Fanger equations, as behavioural adaptation also includes the changing physical activity level and changes of clothing. These are directly implemented through ‘clo’ and ‘met’ rates. The equations and the six factors are implemented into the above evolutionary algorithm with an external interface, allowing the designer/researcher to alter any of the six factors as input into the evolutionary process. The thermal simulation procedure additionally integrates two other models and studies as described below.



Simulation of airflow through the brickwork at different brick rotations and different air velocities. Simulation conducted in Autodesk Vasari. The data from these simulations are then integrated into the evolutionary design model. Screenshot of computational simulation by Isak Worre Foged.

Absorption properties of a selected dark brick were simulated in Autodesk Ecotect 2012 with a successive rotation of 15 degrees in a four-by-four assembly. Absorption data from each rotation were plotted into a scheme for regression analysis. Values were then used along the linear curve to determine near correct values for all possible rotation angles in the evolutionary procedure.

Airflow properties through the brick assembly by rotation were simulated in Autodesk Vasari 2012 with successive rotation of 15 degrees in a ten-by-twenty assembly [Fig. 10.4]. Airflow data from each rotation were plotted into a scheme for regression analysis. Values were then used along this linear curve, after opening between the bricks by rotation within the assembly, to determine near correct values for all possible rotation angles in the evolutionary procedure.

10.2 Design Experimentation

The above models combined enable the description of the design model. Experimental studies are then conducted to test the organisation of matter based on computation developed by an evolutionary search approach. When simulating the organisation of bricks, the input factors determined by Fanger's equations are, when activated, allowing the organisation to come as close as possible to the desired comfort temperature. During the simulation the model allows alteration of factors in order to observe the changing brick rotation and the resulting theoretically perceived temperatures in the real-time graph representation below [Fig. 10.5][AR]. While clothing rate, metabolic rate, relative humidity and ambient temperature are freely adjustable by the experimenter, perceived air velocity and radiant temperatures are a consequence of the brick rotation modifying these two factors dynamically. The graphical simulation output also illustrates the peak fitness of a brick in the assembly and the fitness of the whole assembly. By this process, it is possible to observe how the evolutionary mechanisms gradually alter the individual bricks towards a formation that, combined, approaches the thermal environmental intentions of the maker. The experimentation includes the modification of the six factors to identify the thermal and visual impact on the envelope as it gradually appears by simple brick rotations. The evolutionary search model and its variables are defined by:

$$
\textit{Thermal Tectonics } 2 \begin{cases} \textit{Minimise} \quad f1_{(xrot,\, met,\, clo)} = PPD \\ \textit{Maximise} \quad f2_{(xrot,\, met,\, clo)} = OPtemp \\ \textit{subject to} \quad 0 \leq xrot \leq 360 \\ \qquad\qquad 0 \leq met \leq 3\,(\textit{dynamic input}) \\ \qquad\qquad 0 \leq clo \leq 3\,(\textit{dynamic input}) \\ \textit{Mutation rate} \quad 0.2 \\ \textit{Population size} \quad 100 \end{cases}
$$

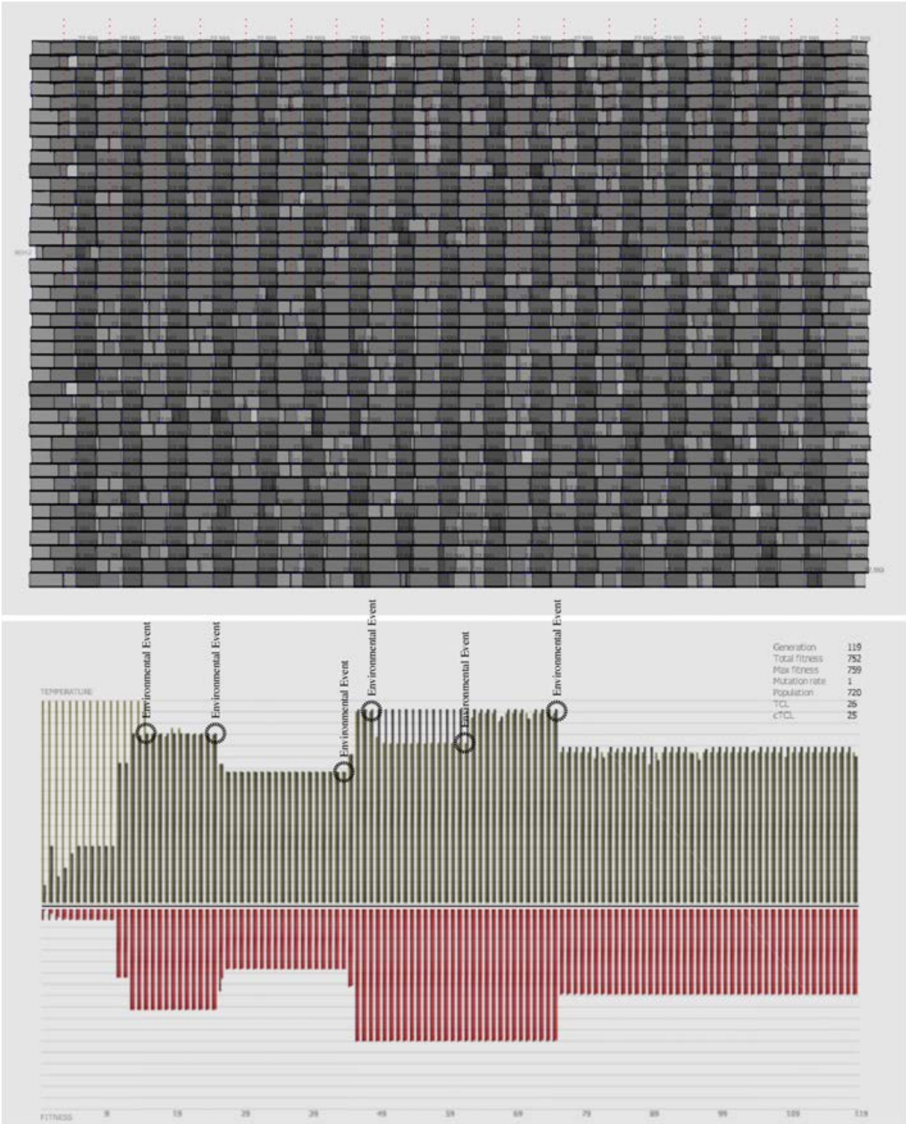


Figure 10.5

Developed graphical interface enabling the observation of the progressive procedure towards the articulation of brickwork and the perceived thermal environment. The green graph illustrates the relation between comfort temperatures and perceived temperatures. The red graph illustrates the fitness score between the current generation and the theoretical max fitness possible. The markings indicate where values have been changed by the designer. Diagram by Isak Worre Foged.

[AR]

10.3 Results

With the intention to study how evolutionary processes can become instrumental in the organisation of matter towards the articulation of perceived thermal sensations for humans, a set of findings related to the research questions is stated herein. Specifically, the study finds that:

(1) Design instrumentality with a dynamic search aim can be created by evolutionary processes. By creating an architectural design method that allows the factors constituting parts of the fitness function to be changed by a designer during evolution, a potential for a dynamic and non-deterministic search is created within an evolutionary search algorithm. In the experiments with the above method, variations based upon the evolutionary method illustrate capacities to progressively modify the envelope to compensate for changing climatic and human properties (clothing/activity) information. For instance, the radical change between an input of metabolic rate = 2.5 and clothing rate = 0.3, simulating a typical sports activity carried out in sportswear, can be compared to the opposite, where metabolic rate = 0.6 and clothing rate = 1.6, simulating a typical office environment. When a new fitness search is defined, the brick assembly gradually alters its brick rotations.

(2) Architectural fitness as approached by the presented method and model is a plateau of solutions, not a singular optimum. Depending on the six-factor combinations, it takes the adaptive process 20-50 generations to arrive at a near-‘steady state’ where only larger variations occur from mutations in the genetic algorithm. This, however, does not mean that all bricks have the exact same rotation. With input factors with low temperatures, clothing rate, metabolic rate, air velocity and humidity, the bricks rotate between 5 and 15 degrees. With opposite high values, the bricks rotate between 35 and 45 degrees. This indicates that, rather than finding an ‘optimum’ solution, the adequate solutions are positioned on a fitness ‘plateau’ allowing a more flexible application of the computed solutions. Furthermore, the cause of the non-equal rotation angle, even after several generations have passed, can be explained within the balance of the comfort equations and the changing exposure area of the brick when rotating. As the brick rotates, it alters the absorption capacity in a positive direction. At the same time, after a certain angle, air is passed through between the bricks, resulting in a cooling effect. The implementation of the two factors with the brick assembly works to some extent in opposite directions. This means that bricks with rotations within a narrow domain can have the same fitness level and thus there is no thermal causal reason to modify further.

(3) Comfort temperatures are not necessarily achieved by porous brick formations. From the temperature indicators [Fig 10.5], it can be noted that the comfort temperature and perceived temperature do not always equal out by the evolutionary process. This can be caused by the brick assembly’s inability to alter the thermal environment sufficiently to accommodate the differences between the computed general comfort score and the individually perceived operative temperature.

Figure 10.6

Final full-scale brickwork demonstrator build next to the Utzon Center, Aalborg. The brickwork illustrates a visually and thermally perceived deep envelope. Photo by Henrik Christensen.

Returning to the research questions, it can be stated that a non-deterministic framework for an architectural method can be described when an external influencer alters the factors and relationships that determine the search. In relation to the second question, it can be argued that different matter states, when described and implemented into the method, have an interdependent effect on each other and the overall perceived environment and articulated organisation. This is particularly visible when observing the reciprocal effects of thermal energy reception related to the material properties of the brick and airflow based on the solid brick rotation.

10.4 Conclusions

The study presented is developed through an evolutionary process integrating thermal environmental simulations and the ability for a designer to interact with the developmental process by modifying the variables during the design search. The four causes are, as previously stated, used to evaluate the probe as an approach to Environmental Tectonics.

The thermal simulation is based on a series of environmental and human factors, which have been stated by their matter properties. These include three levels of perceived matter: (1) brick as a building membrane material, (2) clothing as a human attached membrane and (3) moving air and radiation as a determinant of the thermal environment between the two membranes. By modifying the clothing and brick assembly, the thermally perceived environment is modified. The causal relations between the three levels of perceived matter, causa materialis, therefore bear an explicit relationship to the human sensations. However, a temporal revealing of material causal relations could, potentially, be articulated further if the materialisation of the envelope were based on a progressive selection process of matter, as seen in the previous two studies in chapters 8 and 9. The clarity of the formation process, causa formalis, achieved by simply rotating the individual elements, is argued to cause an explicit and discernible reading of the envelope's formal and thermal appearance. The evolutionary algorithm, despite its stochastic behaviour, appears to advance the formation in steps that are more readable than the ones observed in the first two studies, presented in chapters 7 and 8. The cause of the final form, causa finalis, illustrates the intention of an open envelope articulation based on both visual porosity and permeable thermal transfer. The causal effect, causa efficiens, of the probe is visually registered from a distance, while the thermal effect on sensations is only readable in close proximity to the envelope. The cause for this is that the thermal environmental mixing happens more intensely the farther away from the envelope it is perceived. As the envelope probe only searches for one condition across its surface, no differentiation within the envelope is created. In larger formations, a heterogeneous organisation could be created to support a difference in thermal sensation along the envelope, increasing its thermal causal effects, as stated by Heschong et al and quoted in the chapter Environments.

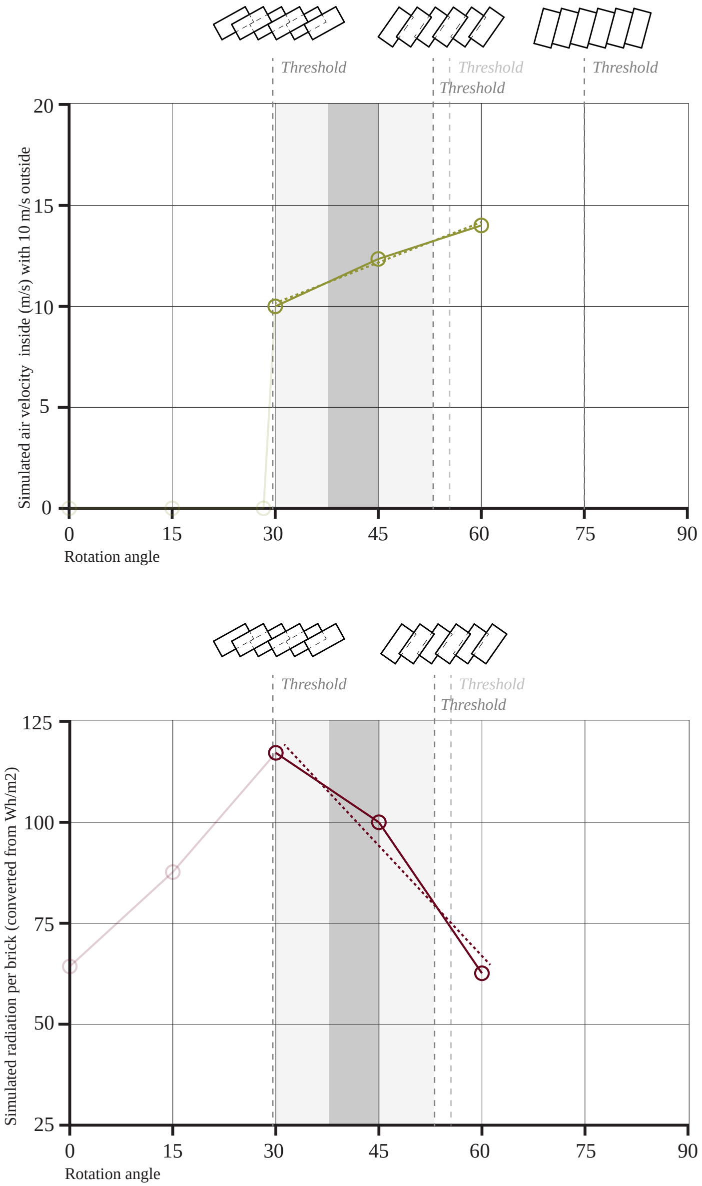


Figure 10.7

Graphs of the brickwork rotation thresholds to maintain structural integrity. The insolation of the brickwork and the airflow through the brickwork becomes thus a function of rotation degree. These values are part of the thermal sensation model. Notice also the changed threshold, which was included after the physical probe was constructed due to a re-evaluated overlay of the bricks in relation to mortar drying time. Diagram by Isak Worre Foged.

Figure 10.8

Frontal view of the deep visual and thermal brickwork envelope. Photo by Henrik Christensen.

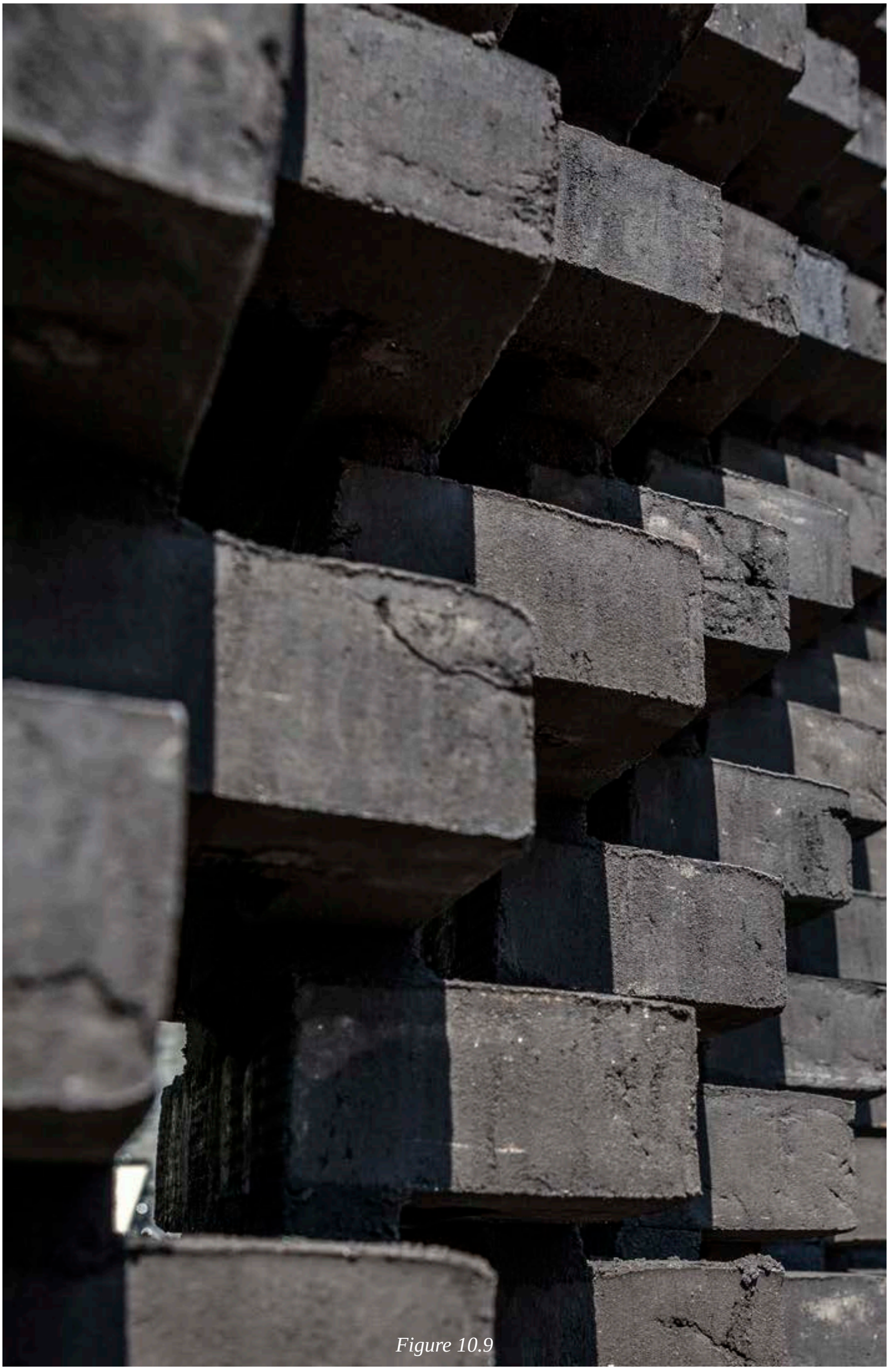


Figure 10.9

Final full-scale probe in detail. Photo by Henrik Christensen.

10.5 Discussion

While the geometric operation of rotating a brick in an array is a simple procedure, it has been shown to have a significant impact on the perceived thermal and visible aspects. The Fanger equations and their extensions enable such an assessment within a computational based experimental approach by integrating the bodily environment (physiological aspects), the behavioural environment (clothing and activity aspects), the conditioned environment (architectural aspects) and the natural climatic environment (microclimatic aspects). From the study above, it has been stated that evolutionary design processes enable new suggestions and understandings of the relationship between a sensed environment and an environmental human-oriented architecture.

It is clear, however, that if we wish to move towards an application of these results to climates other than ones that allow annual air permeability, the brick assembly could be advanced through the use of additional layers, supporting the argument for composite ‘maximum structures’. This is also evident, as the rotation of the bricks was not able to close the gap between the perceived temperature and the general comfort temperature. However, as stated by Nicol and Humphrey (Nicol & Pagliano 2007; Nicol & Humphreys 2002), a general described comfort temperature may be unnecessary in more open and Free-Running Buildings. This, nevertheless, does not imply that architecture should not construct thermal sensations for humans in an extended aesthetic articulation.

In future studies, additional layers could be described in a similar manner to the brick assembly, with the ability to locally change layer properties. This could introduce another operational variable that would support greater control and articulation of the thermal factors. Additionally, rather than using one form of brick, the evolutionary process could take multiple properties into account and suggest a solid matter property, or simply alter the surface colouration, in order to then to let the designer choose a material with this property. The design method is established and can be fed with matter properties other than the one presented here. In addition, an assembly could also be described not as planar organisation, but as a ‘free-form’ surface, which would create a greater search field for both airflow and absorption factors.

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11

Thermal Tectonics III

My interest in envelopes as political devices is that they constitute the element that confines an atmosphere and regulates the flow of energy and matter in and out of a system. If traditional politics are based on equilibrium and closed systems, the contemporarry mechanisms of social and economic integration suggest that systems need to operate in open mode. And, like thermodynamics, equilibrium is only valid for closed systems where the overall amount of energy is kept constant. Once energy flows in and out of a system, the number and type of possible historical outcomes greatly increase.

(Zaero-Polo, 2008:204)

11.0 Preliminary

Humans sleep, eat, play, sit, walk, read, exercise and rest inside buildings. As a result, we as humans spend by far the predominant part of our lives in enveloped spaces that are constructed. Each of these activities requires a particular environment so that sleeping is made more comfortable, reading is made easier, and playing is made more enjoyable. In the case of an architectural structure that does not meet these environmental conditions, there is a tendency to apply machinery, often in the form of lighting, heating, ventilation and air conditioning systems (Moe 2010). These systems often become a form of attached décor, a kind of unwanted architectural ornamentation applied to the structural components of the building. By a technical-mechanical approach, it has been argued previously that the activity or spatial programme has decoupled the articulation of the architecture. Further, the external natural climatic environment has unlinked both the building and the humans inside. What follows is the additional negative by-product of constant energy expenditure to run and maintain the machinery that compensates for the lack of environmental architectural articulation.

It was shown in the previous study that the perception of environment, the climatic environment and the articulation of an architectural envelope could be connected and developed by evolutionary processes. It was, however, also identified that the study did not accomplish an illustration of how such an approach could apply heterogeneous building materials and their organisation as a composite organisation of matter geared towards specified thermal sensations.

The inquiry of this study is therefore to develop an approach to constructing environmental architectures for humans based on multi-material constructions. This approach is part of the combined matter organisation, as described in the previous study, which increases the spatial quality and perceived architecture from an environmental sensory perspective.

The background for previous solutions is based on the previous study, described in chapter 10, and on the ability to understand and simulate both a thermal environment and a design method through progressive steps, as discussed in Fields (part 2) of this thesis. A design advances by iteration, as is the nature of the design process (Lawson 2006), but beyond a few proposals, this study continues the method of applying evolutionary algorithms, whose basis relies on a multitude of rapid iterative processes for progression. Previous work combining thermal simulation with evolutionary programming has been done by Ali Malkawi et al (Malkawi 2005; Malkawi et al. 2005) focusing on Computational Fluid Dynamic (CFD) models and how to optimise the opening of windows and doors in a simple rectangular space. In their studies, they pair a commercial CFD solver with a standard genetic algorithm (SGA) based on an open, accessible programming library. Luisa Caldas et al (Caldas, Norford, & Rocha, 2003; Caldas, 2006, 2008) have performed similar studies by modifying an existing building design towards improved energy scores. This is done by coupling the DOE2.1E energy simulation engine with different types of evolutionary algorithms. Recently, David Gerber et al (Gerber & Lin 2012; Gerber et al. 2013) have worked on more diverse geometric forms than the previous studies by Malkawi and Caldas

Figure 11.1

Brickwork bond combining two similar bricks but with different colours into a composite heterogeneous masonry structure. Photo by Isak Worre Foged.

to apply the approach to architectural design problems closer to practice, by coupling multi-objective evolutionary algorithms (SPEA) with an energy simulation engine. The aim of the study was to improve energy balances and financial scores. As stated in the thesis Introduction chapter, previous research work in this field is very limited and the above references lie on the periphery of the objective of this work, as they focus on bottom-line energy efficiency scores, rather than on the construction of specific thermal environments that subsequently may improve energy balances. Studies by others, organising matter to achieve spatial thermal properties by evolutionary computation, have not, to the knowledge of the author, been carried out before.

It has been attempted in this study to construct an Environmental Tectonic probe on the basis of the above aspect and previous studies and conclusions. The design model is constructed of three interacting models: an environmental simulation model, an evolutionary model and a parametric model. The core investigation aims to explore the capacities for a multi-matter brick envelope and the effects of the matter organisation defining the perceived sensations.

From this, the study presents the theory and methods of perceived thermal environments for humans and how these are applied into the specific evolutionarily based design methodology. Following the description of the computational methods used and developed, a preliminary study is performed as an elementary setup to illustrate the method as a design approach. Based on this provisional example, a pavilion structure has been developed to construct a larger envelope with different climatic environmental orientations to test the ability to construct differentiated environmental formations across the envelope.

11.1 Methods and Models

Similar to the previous study, three computational models are combined into one experimental research model for evolution-based development of environmental-human constructions.

Environmental Simulation Model

In relation to the environmental simulation model, a new thermal solver has been developed, written in the programming language C#, to enable a fast iterative assessment for conceptual architectural design processes. The solver is directly applicable to the 3D modelling software Rhinoceros and the parametric modelling plugin Grasshopper. It was chosen to develop the solver as an extension of the previous environmental simulation models, as advanced existing thermal simulation solvers, such as BSim, IES and DOE2.1E, require a well-elaborated design before a simulation can be initiated, contradicting the approach of progressive development by evolutionary processes. While early design phase solvers exist, such as the software DIVA, they have too low a resolution of data output, allowing the experimental observer to register only accumulated values, rather than, for example, specified daily and sub-hourly simulation data.

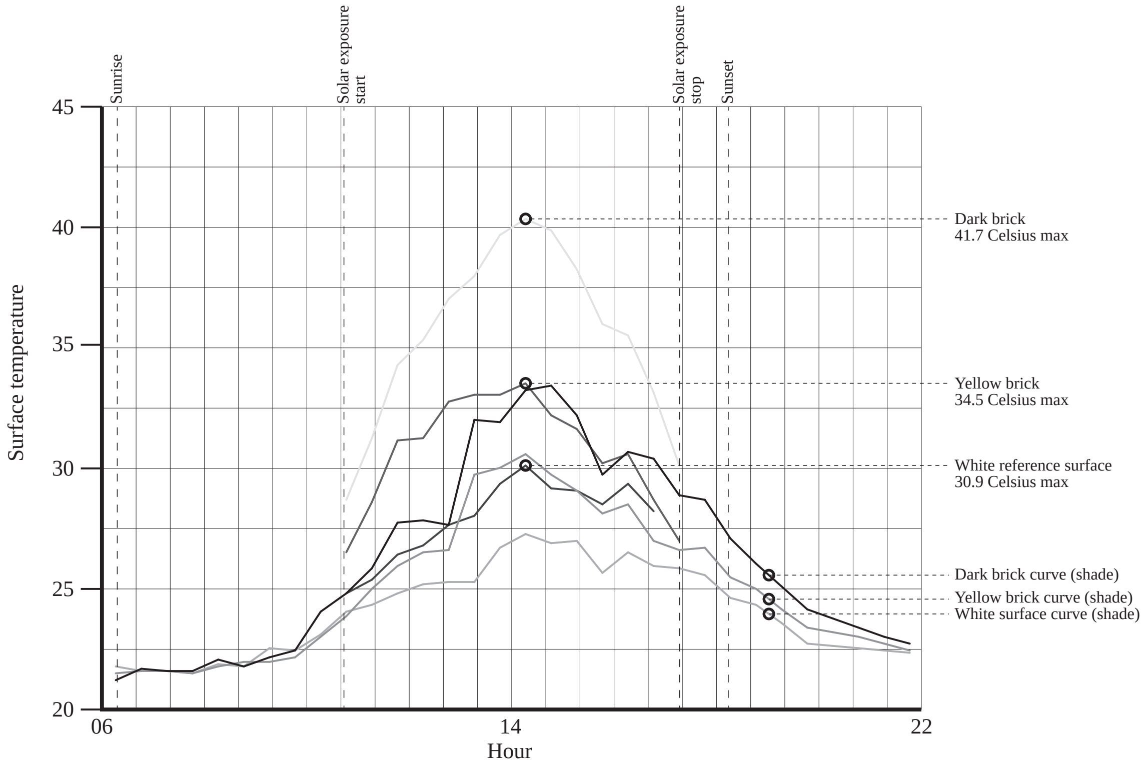

Figure 11.2

The graph illustrates emperically measured temperature deviations based only on colour difference. The measured values are shaded and solar exposed dark and light bricks and a white wooden reference surface inside a triple layered South-East facing window with a clear pane. Temperatures are measured with IR thermometer at horizontal surfaces, 12 March 2015, Copenhagen. The surface temperature close to equinox reaches almost 20 degrees Celsius higher values than the room temperature. Graph by Isak Worre Foged.

The environmental solver integrates the discussed equations provided by Fanger (Fanger 1970b; Fanger 1973) and some of their extended formulations. To further elaborate on the architectural potential of these perceived thermal assessment methods, one can initially consider the human aspects integrated, as the clothing rate says something about the condition a human is situated in. Many people will wear lighter clothing in warm summers and warmer clothes in cold winters. However, this is not always the case, as cultural-social influences may restrict this behavioural adaptation, with a bank being an example in which employees are seldom allowed to walk around in shorts and sandals. We see similar patterns with regard to the metabolic rate, which describes a person's physical activity and is also related to the local climatic environment; humans, for example, tend to sit more densely packed, keeping arms and legs closer to the body core in colder climates and according to the physical activities prescribed by the social situation. Being in a gym class at school simply does not allow a low metabolic rate, as it is determined by a situation in which physical activity is required. Less drastic everyday cases can be seen in the simple difference between the metabolic rate of an engineer at work of Met 1.2, while washing dishes has a metabolic rate of Met 2.5. Architecture may suggest a clothing style and a metabolic rate, but it would be difficult to dictate it.

When considering the environmental aspects, architecture is far more instrumental in the determination of the human thermal sensation. The ambient air temperature is naturally related to the external climatic temperatures unless the architecture is constructed as a thermally sealed container. By heating an architectural construct, for instance using the sun or the Earth, the internal air temperature can be modified by convective processes, in which the air is warmed or cooled and then reaches the human and adds to the perception of a thermal environment. More complex is the radiant temperature, that is, the temperature radiated from the surface of a space, including the direct radiation of the sun in glazed or open environments (La Gennusa et al. 2007; La Gennusa et al. 2005). Several considerations and assumptions must be included, such as whether a person is standing or sitting, body posture and where in the space the person is located, defining the angle factor in relation to the radiating surface. While complex to assess, the mean radiant temperature (temperature based on all the surfaces 'pointing' at a person) and the direct radiant temperature have a significant and interesting affect on humans' thermal sensations. As the sun moves across the sky, it will radiate and heat up surfaces that will either absorb the energy or re-radiate it back into the environment. This forms an interesting and challenging potential for architecture in that the designer can organise solid material to absorb and radiate energy, with the aim of influencing the mean radiant temperature and the resulting thermal conditions for humans. As a consequence, what is organised are states of matter. In this process, the capacity for air movement is determined by the porosity capacities of a given enveloped architecture. Lastly, relative humidity is largely defined by the external climatic environment while also being coupled to the ability to ventilate spaces and change the local humidity conditions by, for example, saturating air with water.

The work here focuses on the ability of architecture to modify the thermal sensation of humans in a specific environment through the articulation of radiant air

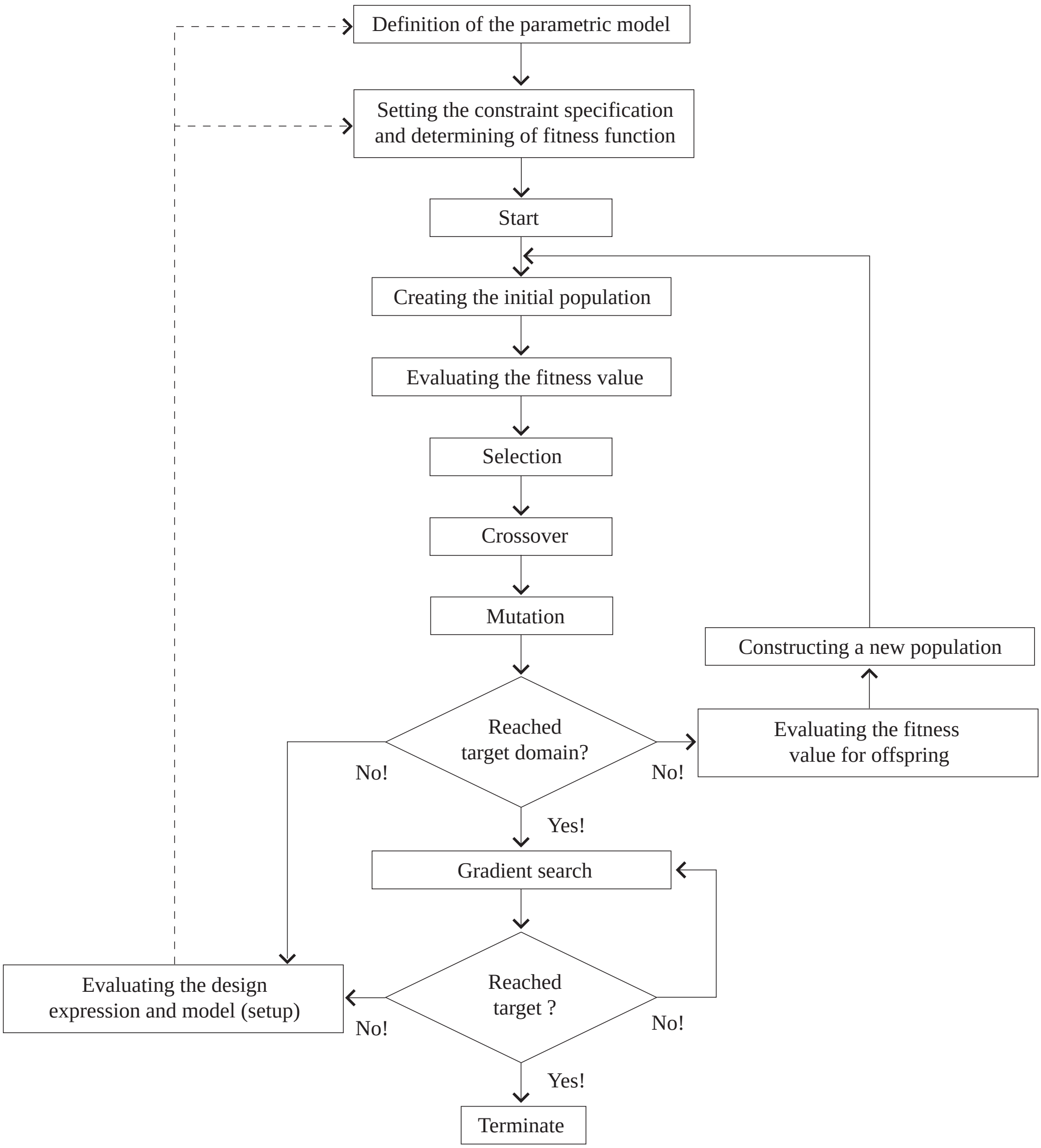

Figure 11.3

Diagram of an evolutionary design model. Diagram by Isak Worre Foged.

temperature. This objective is approached by the organisation of thermal radiation through the distribution of a solid matter, brickwork, in different formations.

The mathematical models on which the simulation methods are based follow the current ISO standards (ISO 2005), but deviate in some aspects, as simplified methods have been used in part of the simulation to allow the simulation to be included in a design loop that requires rapid feedback. The developed models for thermal evaluation include (1) calculation of solar irradiance based on Lambert's Laws for solar geometry and physics (Oke 1987); (2) calculation of insolation on a given surface based on global irradiance, the sun vector and the normal vector of a given surface facing the sky, including detection of self-shade (ibid.); (3) calculation of temperature increase on the external and internal surfaces of an envelope based upon calculation of decrement factor and decrement decay (ISO 13786, 2007); and, finally, (4) calculation of perceived temperatures, comfort temperatures, operative temperatures, predicted mean vote (PMV) and predicted percentage dissatisfied (PPD) based on the original Fanger comfort equations (Fanger 1970a; Fanger 1986; Fanger 1973) and the modifications to the mathematical models (Kerslake 1972; Höppe 2002; La Gennusa et al. 2005).

Evolutionary Model

In design, it is argued (Akin & Lin 1995) that not only iterative but rapid iterative processes of 'sketching, analysing and synthesising' increase the ability of the designer to create novel design decisions. As argued, the principle of evolutionary computational processes is the rapid iterative analysis of an element in relation to a defined environment. This adds to the previously stated arguments in favour of applying a progressive search methodology in architecture. Thus, evolutionary processes in this study are interesting, not only to optimise a pre-existing design oriented towards an optimum solution, as is the tendency in engineering processes (Rao 2009), but also to explore potential phenomena and computed proposals that lead to novel design decisions. This is an aspect that was also examined in the previous study, chapter 10.

While they have been applied predominantly in the sciences, the processes of evolutionary simulation have also caught the attention of the philosophical field (DeLanda 2001; DeLanda 2011), as the processes capture the complexity of non-linear organisations present in other creative processes of design. Since the early explorations by John Frazer (Frazer 1995) in architecture, many architectural and specifically architectural engineering researchers have studied the behaviour, applicability and methodological potential of evolutionary processes, as has already been noted above and in chapter 5, entitled Computation.

Two search methods of finding thermal forms are applied in this study [Fig. 11.3]. The first is a method, entitled 'global search', that is searching stochastically (evolutionary search), meaning that it uses a form of random search, much like looking arbitrarily in all directions to find something of interest. This method covers the 'landscape' of possible solutions and simulates the initial design process in which solutions and problems are commonly defined vaguely. During the search, a series

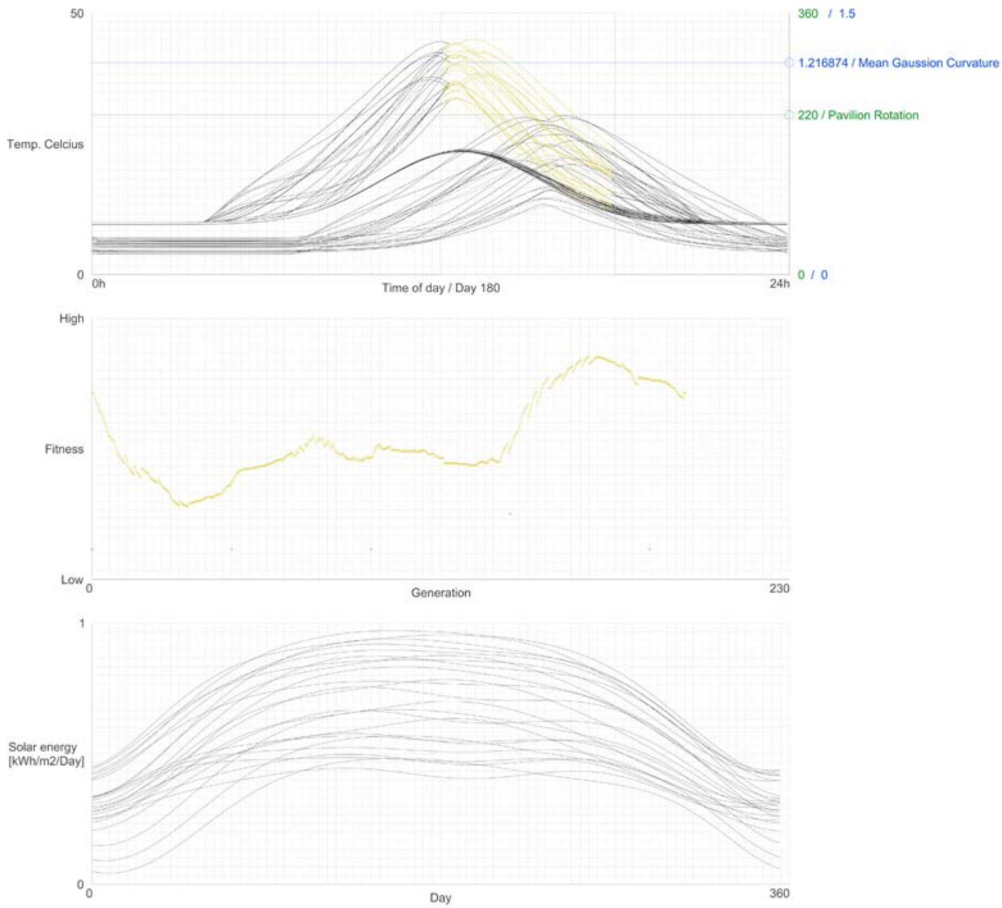

Figure 11.4

Graphs plotting simulated thermal aspects visible to the designer to understand and modify the design variables and evolutionary process mechanisms in order to explore the initial design and the possible space for design solutions and problems. The graphs represent simulation of 24 points across 24 hours on a specified day and simulation of energy absorption across the entire year. It is possible to illustrate a region or all bricks of an assembly at the same time in the graph so that the designer can filter the amount of information needed to improve the understanding and design proposals. The remaining graph points and curves, omitted here, illustrate the data output from a group of point/brick simulation pass. The top graph illustrates ambient temperatures from the dataset and calculated surface temperatures, operative temperatures and resulting PPD. Within the extensive set of information, an architectural thermal intention can be formulated and made operational for the computation process. Screenshot of computational simulation model by Isak Worre Foged.

of potential solutions and problems can be detected, along with the design variables that are adjusted to get there. This narrows the search field, or design solution space, and the design variables can be more precisely formulated in relation to the design objective. A 'local search' (gradient search) method is then applied, which, instead of looking in all directions all over the design space, only looks nearby and in more fixed directions (Rao 2009). This two-step search approach allows for both a covering of a large quantity of design solutions and the possibility of finding incrementally better solutions for the intended aim of the design according to the fitness criterion, which in this case is a desired thermal sensation at a given time period. The evolutionary procedures in this study are applied through the open-source evolutionary solvers integrated into the Grasshopper framework developed by Rechenraum (Rechenraum 2013) utilising the open-access algorithmic library NLopt.

Parametric Models

The parametric model is created from an initial catenary geometry developed by Dave Stasiuk and Anders Deleuran during the Utzon(x) Summer School 2014, which again is based on the integration of the physics solver Kangaroo, developed by Daniel Piker (Piker 2013). The parametric model is 'inherited' as an experimental starting point and redefined parametrically for development by the environmental simulation model and evolutionary processes.

Brickwork has been chosen as a simple geometric element, yet with a high capacity for varied formations and with thermal capacities due to material density and surface treatment. This allows the design method to be tested in a complex solution space. By doing so, a designer can observe the variations of each iteration proposed by the evolutionary design method. In parallel to the architectural model is a set of visual graphs plotting the thermal behaviour of each iteration and how close a 'fit' the evolutionary process is to a desired solution [Fig. 11.4]. By having this double visual feedback, architectural digital models and graphs, the designer is able to explore both architectural visual expression and environmental thermal sensations of the architecture simultaneously. This is intended to increase the observation of discernible steps and potentially unknown phenomena, and to advance the basis for formulation of the variables that make the design space and the formulation of the fitness function that allows the evolutionary simulation to progress.

11.2 Design Experimentation

An elementary model [Fig. 11.5] is created to test the combined models' ability to develop a modified half-overlay brick bond. Two types of bricks are used, a near black and a bright yellow. The geometry of the bricks is the same, so that both 'lying' and 'standing' bricks can be used in the organisation of the assembly. The change of colour effectively changes the physical absorption properties, as the dark brick has a high emissivity factor, while the yellow has a low emissivity factor, that is, the ability

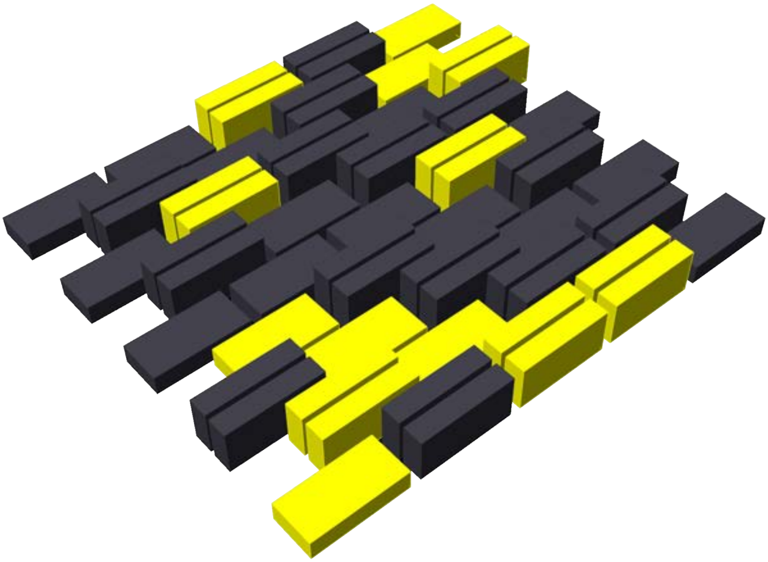

Figure 11.5

Test of a simple digital model for elementary studies of a small assembly of bricks in a half-overlay bond in which the bricks have freedom to rotate, thereby modifying the thickness (thermal mass) and roughness of the envelope and to change colour, thereby modifying the emissivity properties and the ability to absorb and re-radiate solar energy. Screenshot of elementary study model by Isak Worre Foged.

of the material to absorb energy and release it again [Fig. 11.2]. The configuration of 'lying' and 'standing' bricks modifies the thermal mass depth and therefore also modifies the thermal storage and its temperature decrement time. The parametric model then searches for an increase in the operative temperature perceived one meter 'behind' the surface.

Following the initial application of a simple assembly of bricks on a planar surface, the larger and more complex geometry of the Utzon(x) Pavilion is used as a basis for further study. With the multiple thermal parameter output provided from the thermal environmental simulation, it is possible to formulate both single- and multi-objective search processes. Varying the curvature of the vault surface, the orientation of the overall pavilion form, the colouration and the displacement of the bricks within the brickwork bond create the variables that can be modified during a search process [Fig. 11.6]. Intuitively, the surface curvature and orientation of the geometry affect the ability of the architecture to receive solar energy at different surfaces at different times of the day and year, while the change of colour changes the emissivity properties. Empirically [Fig. 11.2], the latter has a profound effect on the change of surface temperature on the externally solar energy-exposed surface and a profound effect on the ability to transfer solar energy to an internal surface from which heat is radiated into an internal space.

The resolution of the simulation points within the model can be adjusted by assessing every brick in the assembly to a resolution of one evaluation point per square meter. Furthermore, groups of simulation points can be selected to create a simulation of a selected area. The study uses the reduced simulation resolution, applicable to the specific study of early design phase explorations. This decreases computational costs and allows the designer to observe a set of desired graphs in order to better understand and develop a design search procedure. Simulation data is plotted for each simulation point for every 15 minutes across the day and year and organised into data structures that allow the designer to select specific aspects, such as envelope external temperatures in specific time periods. This in turn enables the formulation of a fitness function that is directly related to specific thermal conditions within the model. To extend the instrumentality and readability of the progressive search process, each simulated segment of the pavilion geometry is represented by a masonry bond, illustrating the brick displacement and colouration of the, in this study, herring bone bonding pattern. A designer is then able to observe and explore a design process on different design scales, overall geometry, and material assembly and physical characteristics represented in the graphs simultaneously. The evolutionary search model and its variables are defined by:

$$\mathit{Thermal\ Tectonics}\ 3 \begin{cases} \mathit{Maximise} & f1_{(rot, curve, col, dis)} = OPtemp \\ \mathit{subject\ to} & 0 \leq rot \leq 360 \\ & 0 \leq cur \leq 3 \\ & 0 \leq col \leq 1 \\ & 0 \leq dis \leq 1 \\ \mathit{Mutation\ rate} & 0.2 \\ \mathit{Population\ size} & 100 \end{cases}$$

Figure 11.6

The model (top) is divided into a series of segments, with each one having a simulation point. The reduction of simulation points across the surface allows the vast set of calculations to be performed in approximately 30 seconds on a laptop, allowing relatively fast feedback between evolutionary process, thermal simulation and pavilion representation in geometry and graphs plotted. The model (bottom) illustrates the segments laid out flat as building information for the mason. The model updates dynamically between the architectural model and the building information representation. Screenshot by Isak Worre Foged.

11.3 Results

With the intention to study the organisation of matter across a larger enclosing surface than the one used in the previous study, through evolutionary processes, a specific design method, including a new thermal environmental solver, has been presented. This model has then served as the experimental basis for developing an environmental tectonic probe for further examination.

Specifically, the study finds that:

(1) The presented design method and model are able to articulate thermal environmental aspects at both global (formation) and local (element) scales of complex architectural structures by progressive, discernible steps. Through the integration of visual and thermal aspects, an articulation of temporal atmospheric phenomena has been illustrated, moving towards an increase in the perception of both built and natural environments. This leads to an increase in environmental sensory perception resulting in an increase of aesthetic articulation (Heschong 1979) and the production of beauty, according to Böhme (Böhme 2010; Böhme 2005).

(2) The integration of visual geometric and graph feedback to the designer enhances the reading of the form and material development and the ability to reformulate the variables for new search processes. This supports the design relationship between the human making agent, the evolutionary process as a design agent and the environment as a design agent. The aforementioned iterative procedure of sketching-analysis-synthesis is then to be understood as a collaborative process between the above agents, rather than an iteration loop by a ‘single’ designer.

11.4 Conclusions

The study presented a thermal simulation model combined with a two-step evolutionary search process. A geometric model, a set of assembly procedures and a graphical representation of thermal data, computed, revealed the thermal phenomena and progression of the design to the maker. Through these methods and models, an architectural probe was created, which, as a collected contribution, can be assessed in relation to the four causes.

The material properties are extrinsically integrated into the developmental model relating the causal properties of the material, causa materialis, to the climatic environment and the human occupier. The method extends the instrumentality in comparison to the previous study, discussed in chapter 10, as it allows the application of different material properties to solve different aspects, such as energy absorption in one region of the envelope and reflectance in another. With a search procedure modifying the overall geometry and its orientation, surface curvature and surface roughness through displacement of bricks, the causal effect of its formation, causa formalis, is directly connected to the environmental source defining it. Both matter

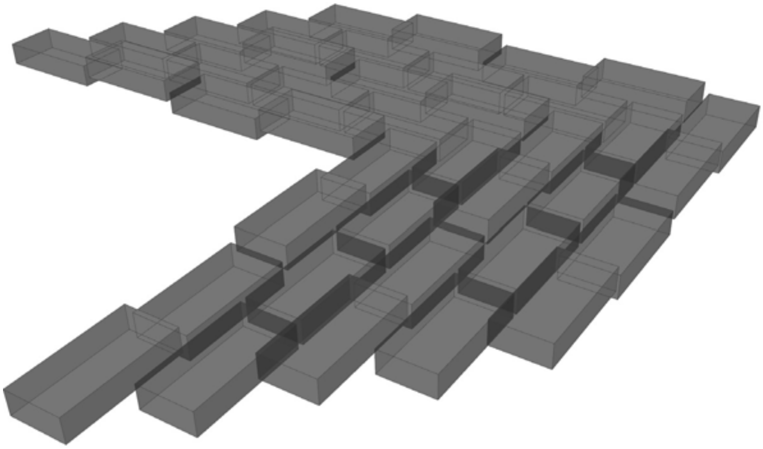

Figure 11.7

Perspective view of a masonry segment in dark bricks. Notice the displacement of every second brick in every second building line . Screenshot by Isak Worre Foged.

Figure 11.8

Perspective view of the pavilion spanning 8 metres in diameter, and the development of pavilion orientation, vault curvature, brick-bound displacement and brick colouration. Screenshot by Isak Worre Foged.

[AR]

application and formal organisation are discernible within the design process. The formation, however, stops after the design progression process, and only negligible modifications to the observed material are present in the brickwork after its physical implementation. So, while the cause of the final probe, causa finalis, is directly related to the cause of the formation process, it stops its transformation, and thus its potential for ongoing visual appearance. In contrast, the thermal causal effects, causa efficiens, are constantly changing, as they are based on the changing climate and the changing occupier. From this, the thermally perceived aspects are in a dynamic process of revealing, even after the design process has finished, while the visual aspects become static.

11.5 Discussion

The application of different thermal matter elements by a change of colour appears to have profound impact on both tactile (thermal) and visually based sensations. When observing the data graph output representing the computed temperatures, a significant change in the external temperature can be observed, while only a small effect is registered in the perceived operative temperature one meter inside the pavilion envelope. This condition is arguably based on the high ventilation rate in the open structure. This leads to the discussion of whether open architectures always increase the sensing of the environment. In this case, the porosity decreases the thermal radiant and the convective impact on the sensing human.

The thermal lag, due to the materialisation and relation to the climatic context, alters the causal effect and thus the conditions for the search criteria logic. With the thermal effect perceived in different tempi, search processes must include information on temporal environmental and occupancy conditions. The cause and perceived effect relationship is displaced in time. The study integrates such dynamics, but without the integration of occupancy patterns, as these dynamics cannot be correlated within the presented search process.

The study applies many operational design variables when compared to the previous study, in which the bricks were simply rotated in a simple array. These variables expand the search space and enable a potentially higher differentiation of elements across the envelope formation. However, while the experiment's applied search processes were creating a diverse colouration across the envelope, it was decided that the physical full-scale probe should maximise the thermal absorption on the outer side of the envelope and minimise the use of dark bricks due to practical aspects of a limited amount of dark bricks available. These fabrication constraints informed the model of aspects other than the sole thermal aspects presented at the beginning of the study as the main driver of the design search. This effectively introduced a 'cost' function, which, it can be argued, bears more resemblance to building conditions in practice.

This chapter has been submitted for publication as:
Foged, I.W. (2015) *Finding Thermal Forms.* New Tectonics Beyond New Technologies. Aalborg University Press.

12

Thermal Tectonics IV

It seems that architects build in an isolated, self-contained, ahistorical way. They never seem to allow for any kind of relationships outside of their grand plan.

(Smithson, 1973:309)

12.0 Preliminary

As stated in the thesis Introduction chapter, architecture needs to address the climatic environmental issues – among others, those raised by local governments (Klimakommisionen 2010) and international organisations (IEA 2009; IPCC 2014), emphasising that the negative impact of the building industry on the natural environment must decrease. Studies examining new levels of sustainable standards imposed by governments show that conventional, ‘static’ buildings cannot meet the energy demands that are involved in reaching the benchmark energy levels of the building fabric (Winther et al. 2009). Additionally, studies demonstrating the relevance and need for humans to be in contact with the natural environment, perceiving the rhythms of days, seasons and years, have been well-documented (Ulrich 1984; EPA 1991; Fich 2014). This suggests that humans desire to ‘read’ the intervention of the environment within the buildings they occupy. Besides the mental and physical health of people in buildings, the change of a building’s appearance anchors the building to its context, supporting the localisation and expression of an architecture and thereby increasing the readability of architecture to the observer (Frampton 1983; Mostafavi & Leatherbarrow 1993). Such a perspective on architecture was posited by Jonathan Hill, who stated that the development of an architectural design arrives from the ‘co-production’ of construct and environment (Hill 2012). Similarly, David Leatherbarrow asserted that a building is never finished, as the material processes undergo continuous change (Leatherbarrow 2009). This allows us to suggest and support the previous proposition that there are at least three aspects at work – the environment, the construct and the human – in the ongoing construction of architecture, which in a reciprocal process affects humans, constructs and environments. The previous research, as shown in chapter 11, identified and elaborated upon a method and model for engendering non-visible temporal sensations with thermally based constructions. It was, however, also discussed that the proposed model and its resulting probe did not maintain an environmental revealing from a visible perspective after its physical construction. In order to address this aspect in a way that facilitates an increased sensation of the environment, this study examines dynamic responsive methods.

Previous solutions for dynamic systems in architecture are rich in terms of the range of solutions presented, from automated conventional window blinds for industrial products to a multitude of mechanical systems (Hoberman & Schwitter 2008), semi-mechanical/material systems (Foged & Poulsen 2010; Foged et al. 2010) and fully material-based systems (Hensel & Menges 2006; Hensel 2010; Menges & Reichert 2012)[Fig. 12.1]. The latter examples, strongly emphasising the hygroscopic properties of wood, have been heavily investigated by the listed authors and many others, leading to similar studies and results of a bending behaviour of thin layers of plywood veneer, varying according to levels of humidity. While studies based on wood structures are based on the anisotropic material properties, other studies have previously been presented based on physical models of combinations of isotropic materials forming anisotropic composites (Pasold & Foged 2010; Foged & Pasold 2013). This study focuses on the relationships and responsiveness between different thermal environments, and how these are articulated based on evolutionary processes.

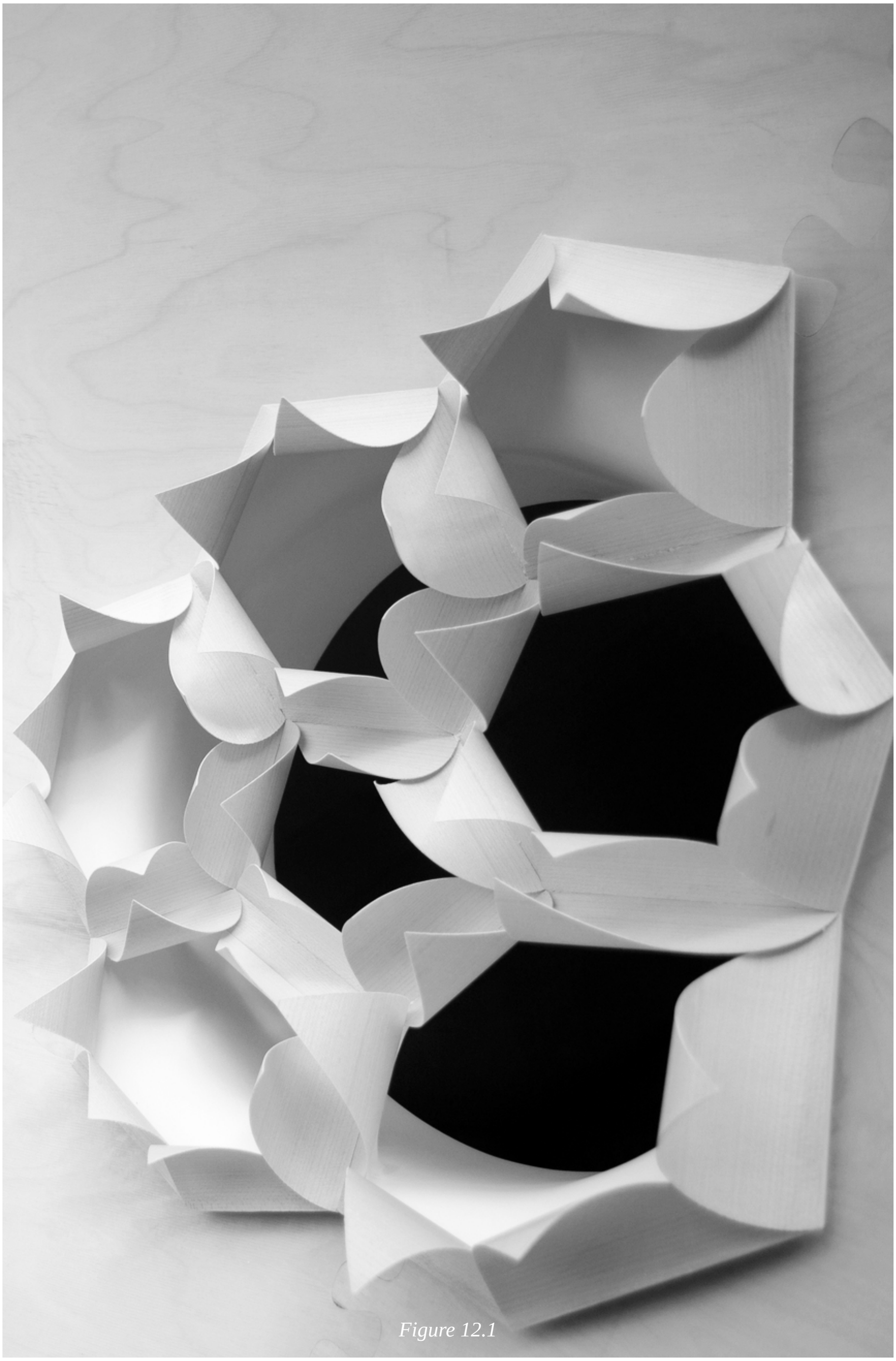

Figure 12.1

Responsive wood model, HygroSkin, by Steffen Reichert, Achim Menges and Oliver Krieg (2013) Photo by Institute of Compuattional Design , Stuttgart.

Through this approach, an indeterminate situation arises for creating multi-material compositions that are powered by the weather and instantiated by the relations between material properties and the exergy situated in the local thermal environment. Acknowledging the need for responsive, dynamic systems in architecture that are constructed of durable material assemblies allows the development of long-lasting constructions, considered an important component in buildings that will be exposed to the wear and tear of the climate. This approach is chosen over mechanical, motorised solutions, which tend to require complex geometric parts and mechanical systems with short life cycles. In addition, the often large quantities of moving parts create friction, wear and tear, and increased risk of high maintenance or early lack of functionality. This approach is also selected over the use of thin, wooden veneer constructs, as these seem to be fragile when exposed to the climate over longer periods of time. They also appear less instrumental in configuration, based on numerous studies, cited by the aforementioned authors, that show the same results of bending behaviour. The background for potential solutions is thus based on the previous studies in relation to thermal assessment, evolutionary processes and the combination of a selected range of metals and plastics, their bonding temperature, the respective geometry of the bi-materials, and the configuration of bi-material elements across the architectural envelope surface.

In the present study, the aforementioned variables related to bi-material composites are investigated with the aim of understanding the interrelations of the material composite, the impact of thermal sensation experienced by humans through the workings of the responsive bi-materials, and the way these factors relate to a specific climatic environment. The intention of the inquiry is to move beyond the current architectural research of isolated material studies, into the interdisciplinary, architectural-engineering scale of material mechanics, environmental effects and human-related perceptions of temporal responsive architectural constructions.

In the present study, time as a factor is explicitly integrated as the property and combined effect of each factor; materials, environments and humans are only understood over time (Hawkins & Blakeslee 2004). Hence, this study focuses on the interactions and relationships, which suggests an instrumental approach to the integration of time-active elements. The research objective is pursued through the integration of a set of computationally simulated processes: (1) simulation of bi-material behaviour, (2) simulation of thermal sensation based on extended methods, with origins in Fanger's method of thermal comfort, and a (3) simulation of an evolutionary process that correlates environmental dynamics, material dynamics and human behavioural and physiological dynamics. Through these studies, the inquiry asks:

How can behaviour be embedded into architectural constructions that consider environmental and human concerns?

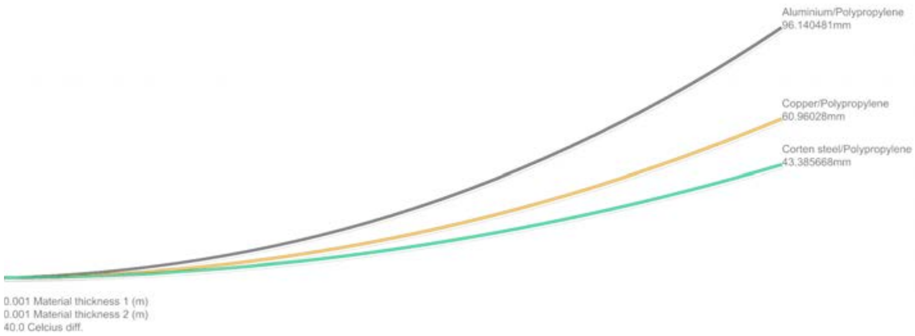

Figure 12.2

Drawing of bending behaviour through bi-material construct as a function of temperature variation. Screenshot of computational model by Isak Worre Foged.

How are methods and constructs prescribed to correlate between the three interrelated agents of environment, construct and human to articulate architectures within a local context, while also improving the constructed thermal environment for humans?

How are evolutionary processes prescribing the correlation of dynamic systems rather than finding steady-state, fixed optimums for an average state?

The above questions are extensions of the research questions raised in the Introduction chapter of this thesis, with a view to addressing the overarching research hypothesis and question.

12.1 Methods and Models

The research uses three computational models combined, including the simulations mentioned above. In order to implement the dynamics of each aspect, custom-programmed modules of each simulation have been created in C# for integration into the Grasshopper software plug-in for the Rhino environment, developed by McNeel Software. Specifically, modules have been created to simulate the bending behaviour of bi-material composites and the thermal sensation of humans in a given space, based on Fanger's equations (Fanger 1970), with updated aspects added to their original form. A standard genetic algorithm (SGA) has also been applied. In addition, DIVA (developed by Solemma LLC), which is based on the Radiance engine, has been used for initial design experiment studies to calculate irradiance levels during the sensitivity analysis of bi-material compositions.

Parametric Models

Three types of metals, Corten steel, copper and aluminium, and one type of plastic, polypropylene, have been selected as the basis for creating composites [Fig. 12.2]. The metals have been chosen based on the criteria of general availability in architecture, implementation and proved endurance as an architectural material, and behaviour in response to thermal changes. Polypropylene has been selected for its general availability, low price, reflective surface when applied as white, and high thermal expansion behaviour. The calculations of bending behaviour are described analytically by the equations 12.1 and 12.2 (Kanthal 2008):

$$\frac{1}{R_T}-\frac{1}{R_0}=\frac{6(\alpha_2-\alpha_1)(1+m)^2}{3(1+m)^2+(1+m\cdot n)(m^2+\frac{1}{m\cdot n})}\cdot\frac{T-T_0}{s} \quad (12.1)$$

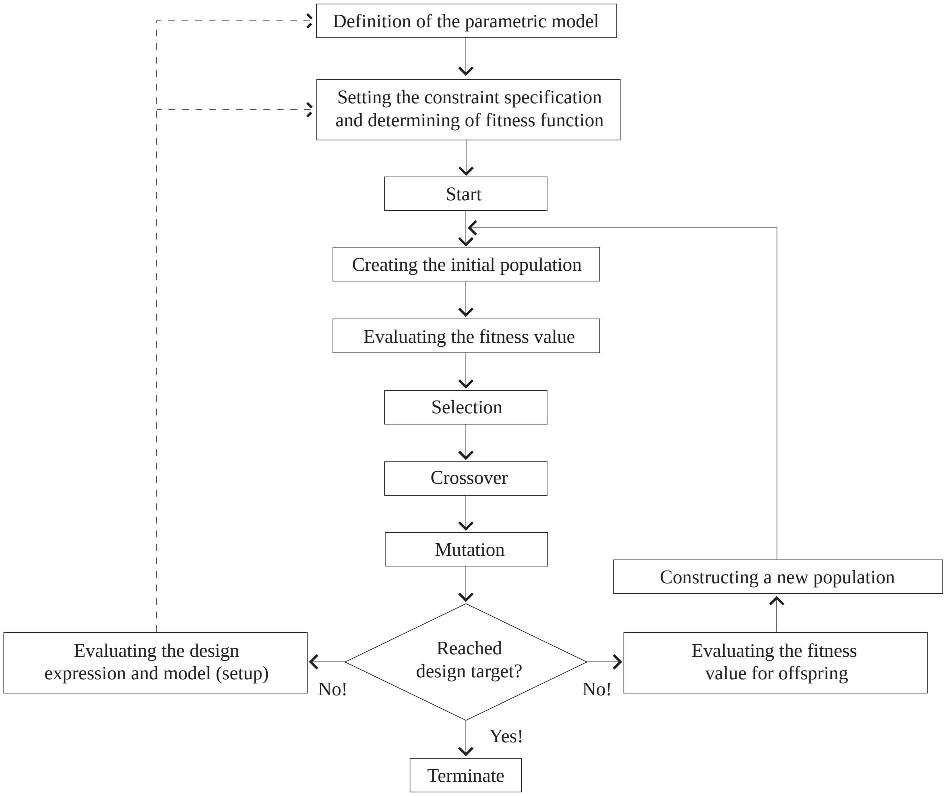

Figure 12.3

Diagram of the evolutionary process applied as an architectural search method. Diagram by Isak Worre Foged.

$$\left(R_T+\tfrac{s}{2}\right)^2=\left(R_T+\tfrac{s}{2}-A\right)^2+L^2 \tag{12.2}$$

The equation includes the variables of the thermal expansion coefficient, Young's modulus, an expression of elasticity, and geometric dimensions, determining the expansion of the singular materials and, when created as a composite, forming the bending behaviour due to the relative difference in elongation between the materials. The bending geometries are then arranged in an array, which creates a surface element that can be configured as an architectural envelope surface by arraying the elements enabled by its 1:2 format.

Environmental Simulation Models

Towards an understanding and integration of environmental-human simulation in architecture, the research looks beyond single-factor studies (Malkawi 2005), such as isolated daylight factors, insolation levels and air velocity levels. These are, instead, combined through the integration of previously described comfort temperature equations. Of particular interest to this work is the radiant temperature factor, determined by the mean radiant temperature, which in turn is determined by the insolation values. The latest research illustrates the increasing importance of this aspect (La Gennusa et al. 2005; La Gennusa et al. 2007; Khamporn & Chaiyapinunt 2013) in relation to the thermal comfort of humans. This in turn promotes the relevance of implementing dynamic constructs in architecture in relation to human thermal sensations and efforts to meet future energy demands set by legislation. The calculations of thermal comfort reach a level of detail that integrates the heat exchange through the respiratory system and evaporation through the skin to the human's physical position and posture in the room.

Evolutionary Model

To employ the approach of a discernible design progression towards material and environmental dynamics in architecture, the study applies a search procedure based on a standard evolutionary process via a genetic algorithm, whose common operators and structure have been described previously [Fig 12.3]. This study investigates, in relation to the evolutionary process, the description of a fitness function for thermal sensations in architecture, which searches time-variable dynamics.

To determine the time-based search function for the design experimentation below, an initial study of an architecturally responsive construct based on bi-materials is conducted. These studies have been conducted with the intent to understand the sensitivity of each variable in relation to the degree of composite deflection. Figure 12.2 above illustrates the bending behaviour of bi-material composites with a length

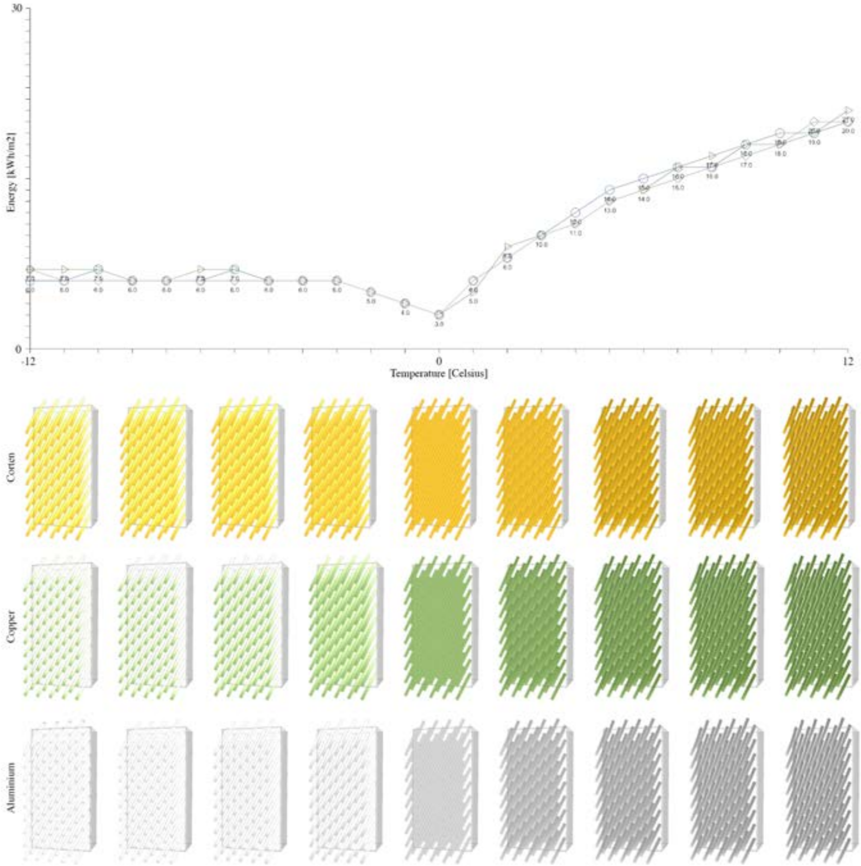

Figure 12.4

Sensitivity analysis of bi-material composites as a function of temperature variation, with the objective of understanding insulation energy transfer through a dynamic responsive bending envelope. Models and graphs by Isak Worre Foged.

of 300 mm as a function of temperature change, varying from 0 to 40 degrees Celsius in ‘bonding’ temperature, the temperature at the time of merging the materials into a composite structure. It is clear through this initial sensitivity study that the largest impact on bending behaviour is induced by temperature variation in accordance with the thermal expansion coefficient of the individual elements. This results in relatively large differences in deflection degree between the composites used.

To study this further a computational model is developed, with an unobstructed, south-facing surface, located in Copenhagen, Denmark, with dimensions of 600x1200mm and populated with 81 bi-material ‘strips’, each with a length of 300mm and a width of 30mm. The structure was situated in front of a glass pane, which is situated in a closed box to block diffused solar energy. Insolation is simulated on the glass pane as a function of a temperature range between -12 and 12 degrees Celsius. Interestingly, there is very little difference in insolation values, despite the difference in deflection between the composites. As the graph of the simulation results illustrates [Fig. 12.4], the insolation is highest when the temperature difference is 12 degrees Celsius, lowest when 0 degrees Celsius, and relatively high at -12 degrees Celsius. In addition, this illustrates that, while the composite has the ability to bend in ‘positive’ and ‘negative’ directions from its planar state, the insolation levels in relation to geometric positions are not symmetric.

The sensitivity analysis showed [Fig. 12.4] that only negligible differences could be observed between different composites in relation to irradiance and, therefore, only negligible effects on thermal sensation were seen. Contrary to this, the effect of temperature when binding or gluing the materials together in relation to a given thermal environment has a high impact, as the gluing temperature sets the ‘zero’ position in which the composite is planar, thereby shutting the underlying space off from the solar energy. From this, it can be deduced that the difference between the bonding temperature and the temperature of the external environment produces the largest impact on a given bi-material deflection, resulting in a given irradiance value, again resulting in the effect of thermal sensation.

The calculated operative temperature and calculated comfort temperature based on the radiant contribution are then creating two ‘positions’ in a solution space. From this, an objective vector can be described, representing the fitness of a given solution at a given point in time, given that the vector is based on the material and environmental conditions at a specific point in time.

This search formulation and environmental simulation allows that the study has accessed multiple relevant output values (operative temperature, comfort temperature and PPD) that can be described as search objectives for the evolutionary process, with only one input variable, the ‘bonding’ (gluing) temperature. This reduces the decision space to a minimum and consequently increases the solution-finding speed. As an example, a scenario could be described for a sports hall, setting the variable of the metabolic rate to 2.1 and the clothing rate to 0.8. This in turn specifies the conditions for a search procedure determining a thermal condition at a specific time or time period, such as minimising the predicted percentage dissatisfied across the day. In this study, either a singular objective vector is used for a specific steady-state time point [Eq. 12.3], or a summation of vectors is used, if a time period is integrated. This is done

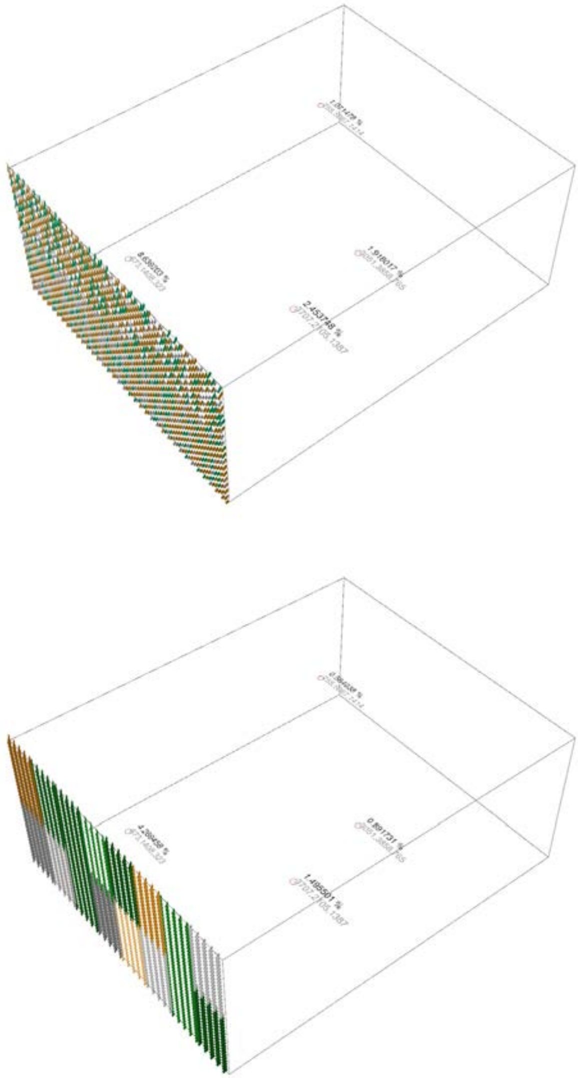

Figure 12.5

Screenshot of computational model of the responsive façade by an array of responsive elements. The top figure illustrates individually organised bending elements, whereas the bottom figure illustrates bending elements nested in modules for assembly. Screenshot by Isak Worre Foged.

by an aforementioned 'preference-based-weighted-sum' fitness function allowing a multi-objective (Deb 2009) search by clustering the summation of objective vectors and search solutions for each of them simultaneously [Eq. 12.4]. This is appealing, as it potentially enables the capacity to devise a dynamic material construct not only in relation to environmental and material dynamic properties, but also in relation to dynamic human behavioural properties. The application of this method is shown in the section below.

$$f_1 = \sum_{i=m}^{n} v_s = v_m + v_{m+1} \ldots + v_{n-1} + v_n \tag{12.3}$$

$$f_2 = \sum_{i=m}^{n} v_i = [(v1_m + v1_{m+1} \ldots + v1_{n-1} + v1_n) + (v2_m + v2_{m+1} \ldots + v2_{n-1} + v2_n)] \tag{12.4}$$

12.2 Design Experimentation

Computational experiments on the thermal sensations in relation to environmental dynamics and material dynamics are conducted based on a summer day in Copenhagen, with a south-facing building surface, allowing the irradiance and insolation data to be obtained from the sensitivity analysis above. The graph below illustrates the external temperature for each hour, with values obtained from the U.S. Department of Energy (DoE, 2014). Relative humidity is set to 55 percent, air velocity to 1 m/s, and ambient temperature to 21 degrees Celsius. These can be dynamically modified. However, throughout the design experiments, the same setup is maintained. Metabolic rate and clothing rate are modified in the experiments below, while mean radiant temperature is calculated based on the integration of insolation values by deflection of the bi-material composites. From this, it is possible to compute various data, including comfort temperature, operative temperature, predicted percentage dissatisfied (PPD) and bonding temperature, as shown in the output graphs [Fig. 12.6]. This provides the designer with immediate visual feedback on the different benchmarks related to thermal sensations perceived.

As a design experiment and an exemplification of the method and model, two different spatial programmes are defined by being used during the morning hours for sport activities and later for activities performed while sitting at a desk. This represents two human activities with very different consequences for the perception of thermal sensation. Seeking to accommodate one of the two spatial activities results in one binding temperature, while the multi-objective search to 'satisfy' both activities results in another [Fig. 12.6]. The evolutionary search objectives and variables are defined by:

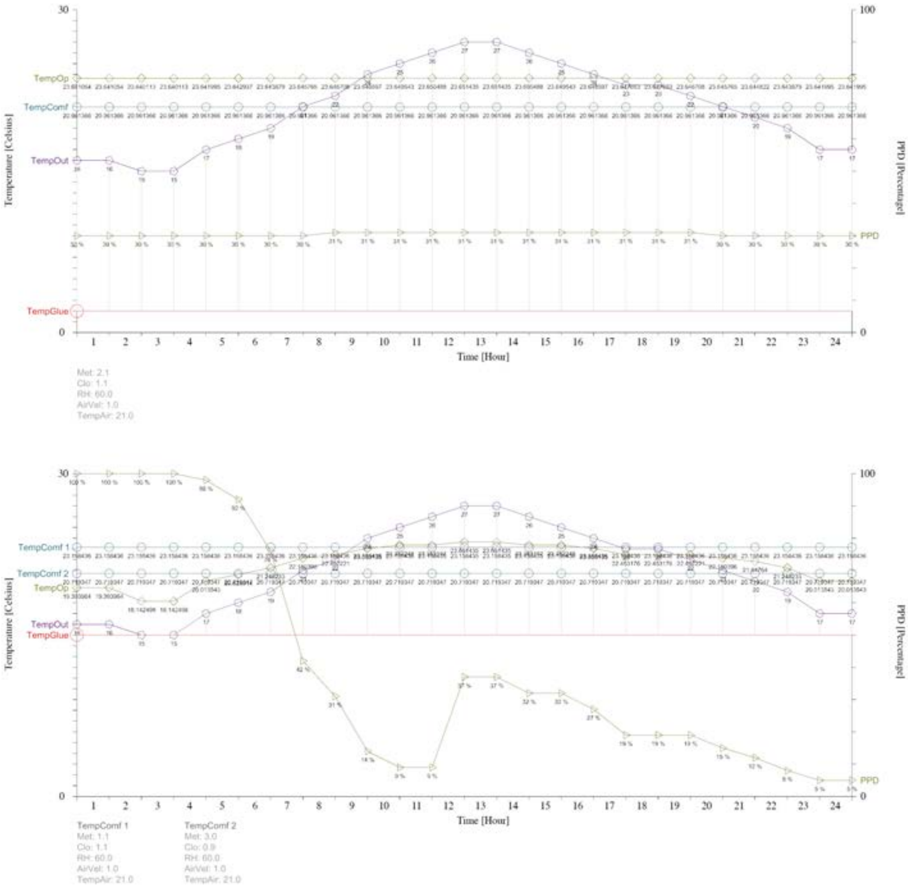

Figure 12.6

Screenshot of simulated temporal conditions during the evolutionary process, seeking the optimum 'bonding' temperature between materials to accommodate holistic and time-specified intentions of thermal sensation (top graph). Illustration of a multi-objective evolutionary process seeking the optimum 'bonding' temperature between the materials to accommodate holistic and time-specified intentions of thermal sensation (bottom graph). Screenshot by Isak Worre Foged.

$$
\text{Thermal Tectonics 4}\begin{cases} \text{Maximise} \quad f_{2(glue,\,rot)} = OPtemp \\ \text{subject to} \quad 0 \leq glue \leq 30 \\ \qquad\qquad\quad 0 \leq rot \leq 1 \\ \text{Mutation rate} \qquad 0.2 \\ \text{Population size} \qquad 50 \end{cases}
$$

12.3 Results

With the intention to study correlations between a dynamic thermal environment, a dynamic material construct and a dynamic human occupancy through evolutionary search processes, the following findings were derived:

(1) The bonding temperature of the composite structure has the largest impact on behavioural properties. This aspect enables a new instrumental matter variable in terms of embedding behavioural properties into responsive composites, besides the known factors included in the equations describing bi-material bending behaviour.

(2) The developed method and model allow the search for temporal material behaviours, which is oriented towards a time-based integration of environmental sensations. This aspect enables the design method to correlate different spatial programmes and integrate, in turn, the ability to articulate thermal-based responsive envelopes in closer connection with the spatial programme of the building. The embedding of specific behavioural characteristics thus points to the notion of 'programming' material behaviour without electronic microprocessors.

(3) The method illustrates an approach to a continuous depiction of the environmental impact on architecture and, from this, its impact on articulating thermal environments. The method and model advance in particularly from the previous study because of the ability to continuously reveal the environmental condition through the envelope response patterns. This ability is, as stated earlier in this thesis, considered a higher architectural articulation (Leatherbarrow & Mostafavi 2005; Mostafavi & Leatherbarrow 1993).

12.4 Conclusions

For a dynamic, responsive system in buildings, the matter organisation suggests an approach of isotropic and durable solid material composites. These properties have a tendency to conflict with the sensibility and material dynamism desired and needed for interaction between potentially influencing agents, such as the environment and humans. However, the bi-material constructs presented have a distinct and perceivable dynamic expression based on material characteristics, causa materialis, proposing

Bending behaviour of the physical prototype made of aluminium/polypropylene composites. Photo by Anke Pasold.

the capacity to be modified and, conversely, modify environments for humans. The presented research illustrates a method by which a designer can embed behaviour into the solid material construct for architectural purposes. The cause of the formation process, causa formalis, is based on the integrated material and the environmental and human factors that are present throughout the evolutionary process, the organisation of matter. Due to the model's responsive properties, constantly changing its visual and thermal impact, the cause of the final form, causa finalis, can be argued to be an ongoing articulation of the formation process. The final form is in constant formation. The close relation of the formation and the final form is a way to perceive the three agents listed above when searching for thermal sensations intended by a designer. What is shown is that the architectural envelope is not necessarily a fixed closure, but a vibrant and dynamic boundary, as we know it from natural systems (Oke 1987). This is suggested to move the proposed design method into time-based, thermally caused sensations as an architectural aesthetic. This, as stated by Heidegger and quoted earlier in this thesis, increases awareness of place and human embodiment and being through architecture (Heidegger 1971). The temporal thermal sensations offered by such a method and model are proposed here to increase the reciprocity between perceived environmental, matter and human agencies in the move towards an architecture that operates based on local conditions.

From the results and concluding remarks, it is argued that the questions in the beginning of this chapter can be positively answered in that the correlation between the described agencies is created through the description of an evolutionary design methodology. Specifically, behaviour is embedded into the envelope by the proposed method and model. This allows the designer to design thermal environments that are climatically environment-specific and adjusted to human behavioural patterns.

12.5 Discussion

With an increasing level of construction specificity introduced through the ability to create dynamic constructs that correlate different agencies over time, a decrease in the general application and thus the robustness of such constructions is apparent. The immediate question is, of course, what if the climatic environment or occupancy patterns change? This is an important question and must be considered in the application of the present approach. Some spatial programmes are said to never change, such as explicitly dimensioned corridors and the like, but often, spaces are used for unexpected activities with different thermal needs and desires. So, while the presented method and probe allow a highly specified relationship to periodic changes, search targets may need to be described for more general conditions in most spaces, in order to avoid a negative effect from unforeseen future occupants due to an over-specified performance outset. Responsiveness, then, is not a question of specificity, but a measure of how well a model can integrate and accommodate known and unknown dynamics. The specificity of responsive behaviour is thus to be evaluated from application to application. This is, as shown, possible by the method described above, the 'weighted' search mechanism. Another approach would be to apply highly

Full-scale prototype of corten steel and polypropylene composite and aluminium and polypropylene composite in the dimension 600x1200mm as elements that can be directly mounted on glazed facades. Photo by Isak Worre Foged.

adaptive models, which would accept any changes to the dynamics of the climatic environment and the human occupancy behaviour.

Another aspect that could be addressed in future studies is the difference between theoretical simulations and the physical behaviour of the probes, and the resulting thermal sensations. This proposal is not intended to change the statement of this study, but rather to calibrate and improve the simulations that underlie the computational work described. In this regard, it is important to note that research is currently being undertaken in the engineering sciences (Gram-Hanssen 2010) to better understand the behavioural adaptation to thermal comfort. The findings from such studies should be included in future human-oriented environmental architectural probes.

Lastly, other methods for manufacturing anisotropic composites from isotropic materials could be investigated in future studies, as the manufacturing process of bonding (gluing) sheets of materials together has a series of challenges not elaborated in this chapter. Such issues include the delamination of layers due to irregularities in the surface cover of the glue, lack of precision when merging the materials into a composite, and problems controlling the bonding temperature, which can hinder the manufacture of the composites according to the proposed design method.

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13

Thermal Tectonics V

Construction does not end the process of articulation, it is its beginning.

(Leatherbarrow 2009:92)

13.0 Preliminary

With an increasing need to address environmental thermal conditioning and energy use, previous research strongly indicates that static buildings do not have the capacity to meet governmental and intergovernmental requirements for energy usage (Winther et al. 2009) and are not meeting the explicit and diverse thermal conditions stated explicitly in building codes and implicitly by building occupants. Approached more ambitiously, architecture could turn this around and offer the construct of environments that seek to accommodate and enrich human life as its primary task beyond building codes, with the additional capacity to improve energy scores. In this way, environmental architecture becomes both the driving element for architectural articulation and a positive influence on sustainable assessment and constructs, currently understood as the task of the indoor climate engineer. The problems mentioned in the thesis Introduction are here restated. The first problem that arises when buildings are environmentally based on pure technical approaches is the physical and mental separation of humans from their context, which has a direct negative physiological and psychological impact on humans (Ulrich 1984; Fich 2014). The second problem is the separation of building and context, limiting the potential for locally articulated architectures, which would aid a move towards a rich and enhanced building culture as a whole (Frampton 1995; Frampton 2011; Leatherbarrow 2009; Moe 2013; Mostafavi & Leatherbarrow 1993).

The background for previous solutions by architectural thermally responsive approaches is roughly divided into two orientations: one focused on the use of mechanical and electronic motor-based constructs, and another focused on the use of material assemblies with perceivable dynamic material behaviour. The former has seen industrial applications from automated blinds to complex mechanical systems, following the early work of Jean Nouvel's Institut du Monde Arabe in Paris. This orientation is typically guided by laboratory studies based on a sensor-microprocessor-material assembly-actuator setup, as can be seen in the work of Tristan Sterk (Sterk 2003; Sterk 2006), among others (Biloria & Sumini, 2009; Foged, Kirkegaard, Christensen, Jensen, & Poulsen, 2010; Foged & Poulsen, 2010; Hoberman & Schwitter, 2008; Mossé 2011). Increasingly in recent projects, these efforts have been applied by large architectural offices such as Foster and Partners in the *Central Market* in Abu Dhabi (2010) and by Aedas Architects in the *Al Bahar Towers* façade in Abu Dhabi (2012).

The latter approach, material-based responsive systems, has predominantly been present in architectural and engineering academic laboratories. In particular, as discussed previously, numerous studies the response of wood to humidity changes have been heavily explored since the early studies by Michael Hensel, Achim Menges and Steffen Reichert (Hensel 2010; Menges & Reichert 2012). These efforts are currently being continued by the above authors and others.

The proposal here and the background for potential solutions are both contained in the previous study, detailed in chapter 12, and the extended experiments with the organisation of isotropic materials into anisotropic behavioural material composites. Instead of using a singular embedded material dynamic, such as the hygroscopic

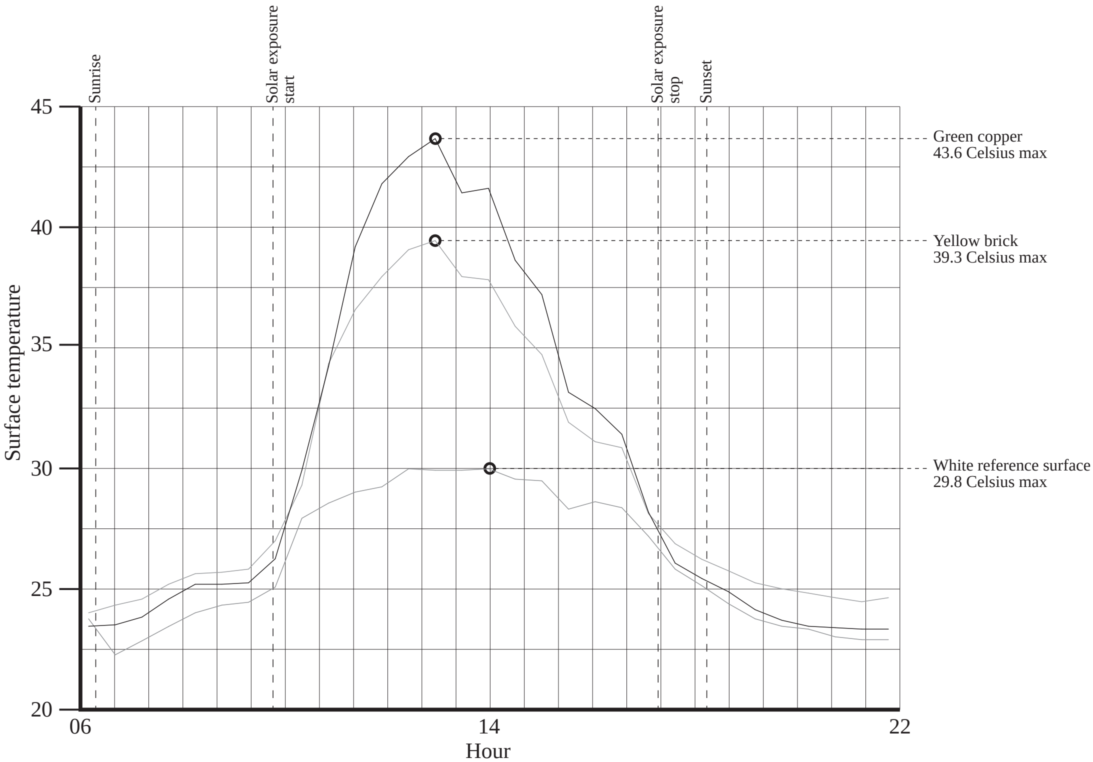


Figure 13.1

Graph of temperature variation based on solar energy across a day near equinox (20 March, 2015). The patinated green copper plate reaches 43.6 degree Celsius, while the brown copper plate reaches 39.3 degree Celsius. Space temperature is approximately 22 degree Celsius. The plates are vertically postitioned and placed behind a window facing South East. Temperature is measured with thermal sensors mounted on the surfaces of the copper plates. Graph by Isak Worre Foged.

properties in wood, this study is based on exploring the dynamic environmental-material properties arising from metal-plastic material composite structures. The previous study showed the capacities for this approach through the development of an architectural method that would search for these material assemblies in response to thermal agency.

What is done in the present effort is the manipulation of assembly composite layers, thereby 'programming' the merged material effect desired towards modifying thermal environmental conditions. Copper and polypropylene are used as base materials for the composite structure due to their high differences in thermal expansion, surface emissivity and temperature alterations [Fig. 13.1], their respective durability, copper's architectural (visual and transformative) aesthetic qualities, as described in the chapter Tectonics, and their accessibility within the industry, making the study directly accessible to others, in opposition to studies based on highly limited and laboratory-based exclusive materials.

The 'programming' of the combined material is approached by altering the relationship (lengths) between the two material layers (metals and plastics with isotropic thermal properties) into a variable composite structure. The research presents the methods used and developed, the way in which the behavioural composites act and perform, and a large full-scale prototype as a demonstrator and experimental setup for post-construct analysis and evaluation of the design research.

13.1 Methods and Models

A set of computational methods and unique modules for the Rhinoceros/Grasshopper computational framework is developed to simulate material behaviour, thermal environmental behaviour and the derived occupancy sensation. These simulations are embedded into an architectural design process model based on evolutionary processes for the development of human-oriented environmental design proposals and computational fabrication procedures for the making of the physical probe.

Parametric Model

The material behaviour [Fig. 13.2] of the two-layered composite is computationally simulated by the use of the equations provided in the previous chapter. Of specific importance are the material thermal expansion coefficients of the two materials, the relationship between the two material elasticities, the material thickness of the combined composite and material length. The former three values remain constant, assuming linear expansion, within the given temperature domain, while the latter, length, is applied as a variable in this specific study. Furthermore, temperature domain at the surface of the material composite is a variable of the immediate thermal environment. The bending behaviour of the composite results from these interrelated constant and variable values. The format of the nested responsive elements differs from the previous study by being organised in a 1:3 module format. This is done to

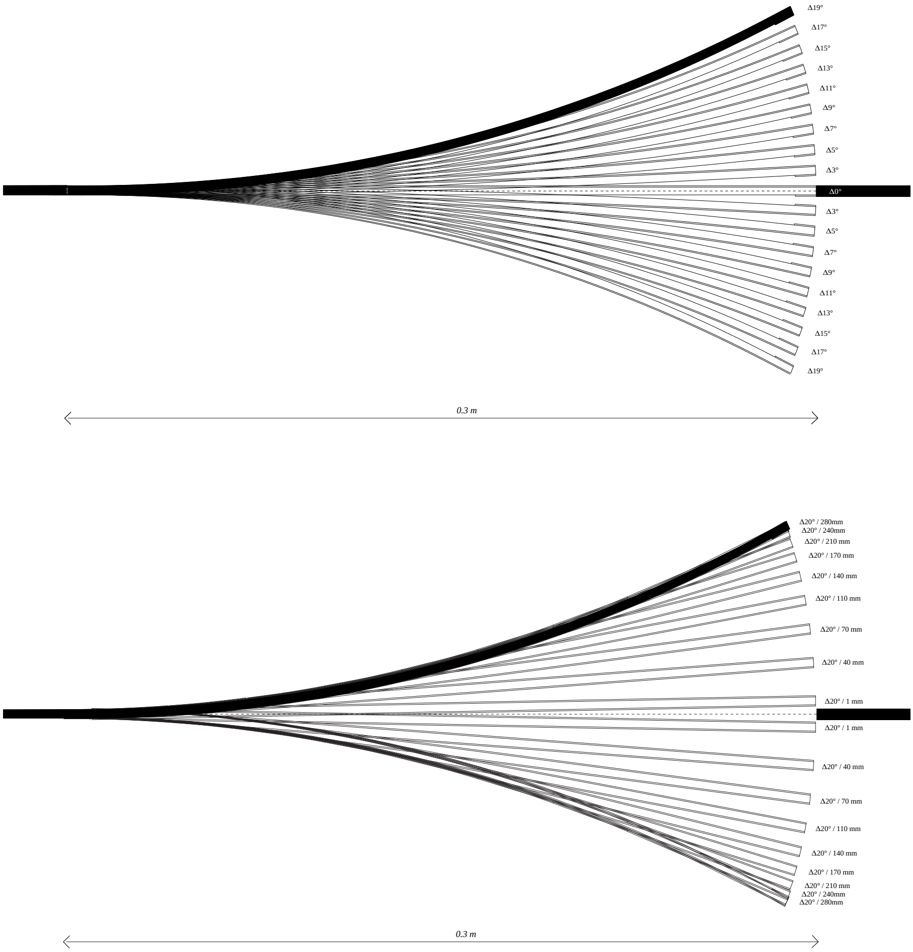


Figure 13.2

Cross-sectional drawings showing the bending behaviour (taken from the computational model) that results from applying temperature and one material layer length of the composite structure as variables (bottom) compared to when only temperature is integrated as a variable (top). Notice the non-linear bending behaviour with linear modification of the variables. Drawings by Isak Worre Foged.

investigate the application of another modular organisational system by the Element, System, Formation methodology.

Environmental Simulation Model

The thermal environmental sensation is simulated with insolation and ambient temperature as input and operative temperature as output. The simulation model is based on the mathematical models described within the previous chapters. The thermal simulation serves as an exploratory feedback mechanism by focusing on specific perceived temperatures to guide an evolutionary search. Thus, the method and model are open to architectural intent, rather than the search for generalised comfort temperatures.

Evolutionary Model

The open-source evolutionary solver *Goat*, developed by Rechenraum (Rechenraum 2013), is used for these studies. When the search algorithm is paired with the above simulations, it advances its architectural thermal proposals by modifying the material composite organisation. Specifically, by changing the length of one of the two layers, the responsive behaviour as a function of temperature variation is explored. This then initiates the development of an organisation of composites that is the makeup of an envelope oriented towards a desired thermal sensation on the inner side of the envelope.

By articulating dynamic matter properties through custom composites and integrating time-based thermal sensations (interrelations between material, environment and human occupancy), the method and model attempt to allow a deep time-based co-organisation of both immediate and offset thermal and visual sensations. This is caused by both instant and delayed conditions as a consequence of the matter dynamics within the model. Such effects were also studied and discussed in chapter 11.

13.2 Design Experimentation

A computational design experiment is conducted to apply the developed architectural model to environmental search processes. The model enables computational testing of the search procedure, progressively subtracting material from the initial three-layered composite. This process creates the basis for a full-scale physical demonstrator. By using the above methods and models to define responsive behaviours, two milling patterns of the three-layered copper-polypropylene-copper (0.5-3-0.5mm) composite material are developed. These include a milling pattern removing a series of areas of the 0.5mm copper layer on one side and a milling pattern cutting through the entire composite along three of the four sides of the areas removed by the first milling

Figure 13.3

Light green copper plate from patination processes. Photo by Isak Worre Foged.

pattern. By this method, the new specific composites are ‘released’ from the base three-layered industrially produced composite into the new two-layered composites, while remaining in a structural lattice [Fig. 13.4]. As mentioned, the overall composite geometry is constructed in a 1:3 format, allowing the panels, as elements, to be arranged in a multitude of configurations as an additional instrumental variable when searching for thermal environmental conditions during the design process. The evoluritonary search model is defined by the below search description and variables:

$$\text{Thermal Tectonics } 5 \begin{cases} \text{Maximise} \quad f_{1(glue,length,rot)} = OPtemp \\ \text{subject to} \quad 0 \leq glue \leq 30 \\ \qquad\qquad\quad 0 \leq length \leq 300 \\ \qquad\qquad\quad 0 \leq rot \leq 1 \\ \text{Mutation rate} \quad 0.2 \\ \text{Population size} \quad 100 \end{cases}$$

To monitor the thermal variations within the prototype, three enclosures are made, each with a set of temperature and light sensors installed at the location of the envelope and in the back of the enclosure [Fig. 13.7]. These register a temperature (Celcius) and light level (Lux) every 60 seconds, creating a high frequency reading of the thermal environment [Fig. 13.6].

Three such enclosures are created, each with a different set of computed and fabricated behavioural panels. Furthermore, on one of the enclosures is an external transparent screen installed to encapsulate the thermal environment [Fig. 13.5]. This is done to study how the composite behaviour and thermal environment may react in a potential double-layered envelope.

13.3 Results

By studying the organisation of isotropic materials by evolutionary processes, the presented method and model have shown the capacity to ‘programme’ material behaviour towards the creation of environmental sensations in architecture.

Specifically, the study finds that:

(1) The developed subtractive method can create a ‘programmed’ responsive composite architectural envelope. By the simple modification of the length of one layer in the composite, advanced behaviour and capacity for thermal articulation are identified and shown. The work finds that the composite organisation (material difference and composite structure difference) has a significant influence on thermal sensations and the visual effect. This can be seen both in the plotted graphs [Fig. 13.6] based on installed thermal sensors and by direct observation in the full-scale prototype [Fig. 13.8 and 13.9].

Copper plate after first and second milling patterns embodying and releasing the behaviour of the new composite structure in relation to the thermal environment. Photo by Isak Worre Foged.

(2) The organisational method of nested modular elements with nested responsive composites enables a modular building method with embedded transformative (responsive) properties. By nesting the composites in modular nested arrays, the method and model are further instrumental in their versatility of application and modification by simply changing the organisation of composite structure and array organisation. The simplicity of the modular Element, System, Formation method extends, in turn, the responsive capacity of the nested composites by allowing various configurations of the composites.

13.4 Conclusions

The study extends the research presented in the previous chapter by exploring the materialisation of a composite structure through the configuration of its isotropic layers. From this perspective, the causal relationship beneath the formation procedure, causa formalis, is similar to the previous study. However, whereas the formation was caused by modifying the non-observable bonding temperature in the previous study, this study's formation principle is based on the direct reading of subtractive processes, creating the behavioural properties of the composite. This is also argued to increase the reading of material causality, causa materialis, as the perceivable change of the composite materialisation is available to the observer. Similar to the previous study, the reason for the final expression, causa finalis, is directly based on the local specific conditions, as the final form is a constant expression of the changing thermal environment. As the copper undergoes the visible and thermal transformations, as described in chapter 4, Tectonics, the causes of its formation, its ongoing materialisation and its final form are argued to become increasingly connected and discernible. The consequence of this increasingly interconnected relationship then has a direct influence on the cause of its thermal and visual effects, causa efficiens, on humans.

13.5 Discussion

The work contributes to the efforts to advance architectural methods and models towards an human-oriented environmental architecture that is rooted in a search for environmentally perceived sensations. In contrast to mechanical electro-motor-based systems, environmental registration and actuation is created as an integrative instrumental composite structure. While it does not allow for a re-configuration of behaviour, as is possible with cybernetic models, it includes the capacity to 'programme' immediate and delayed response patterns that can be orchestrated with human behavioural patterns.

Additionally, a transient and dynamic architecture is supported by the environmentally open and responsive properties of the architectural envelope. Such an approach contrasts with the isolation principles described as the predominant approach today with its described problems listed in the thesis Introduction. In advancing the

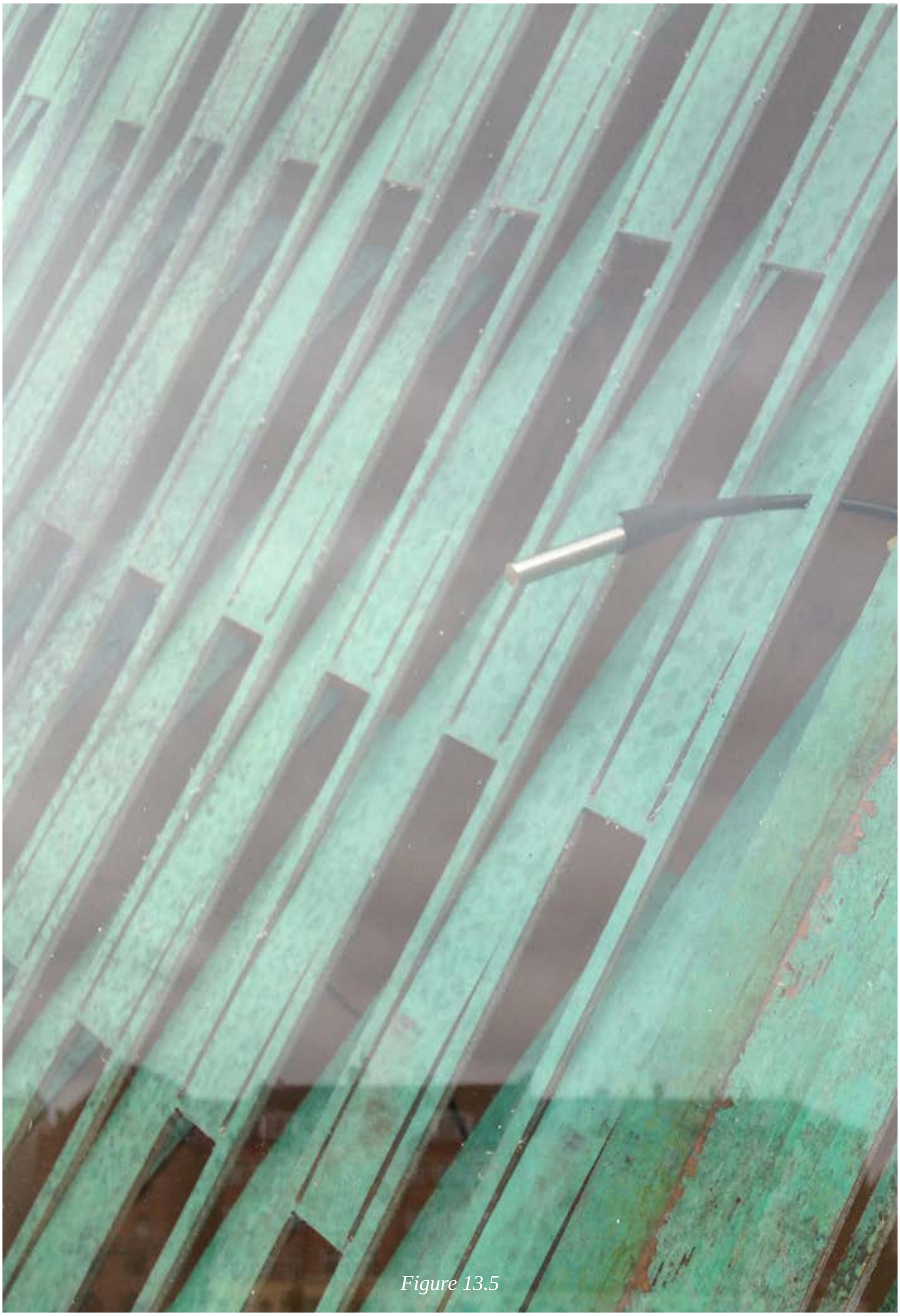
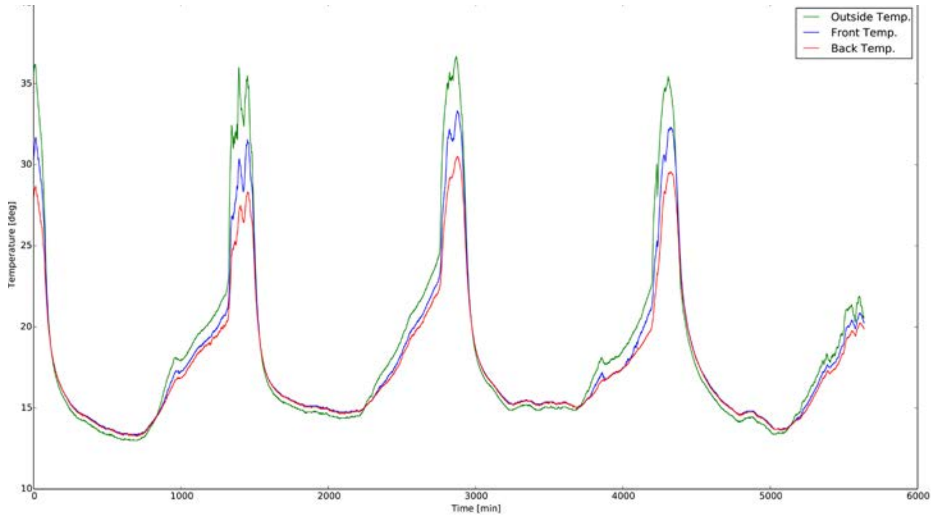


Figure 13.5

A case with a transparent acrylic plate installed on the outer side of the envelope. It is here possible to see the thermal and light sensors installed between the acrylic plate and the copper membrane just above and to the right of the image centre. Viewing the membrane through a transparent plate also modifies the visual appearance, as reflections of the context become visible. Photo by Isak Worre Foged.



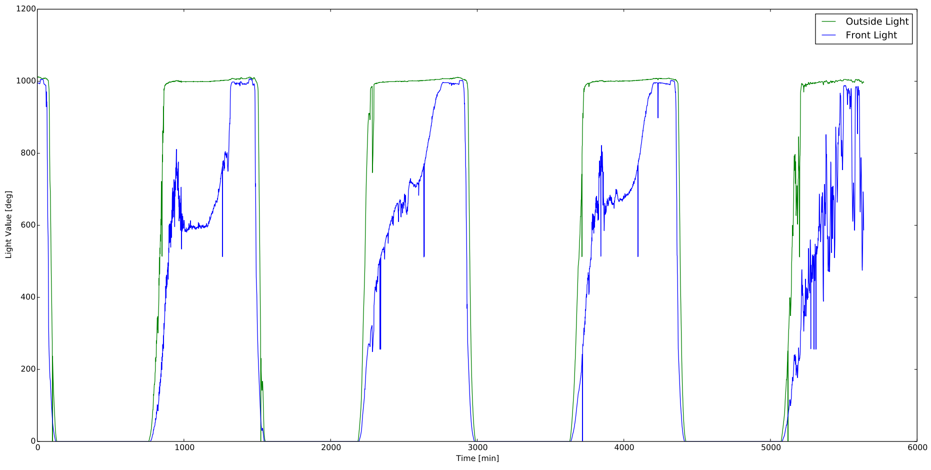


Figure 13.6

Graph of plotted temperature values (top) and light values (bottom) across four days in the cluster with an external screen attached (as seen on page 362). Visible, among other things, is the effect on the composite behaviour of the transparent screen as an increase in temperature and light is registered. Graph by Kasper Worre Foged.

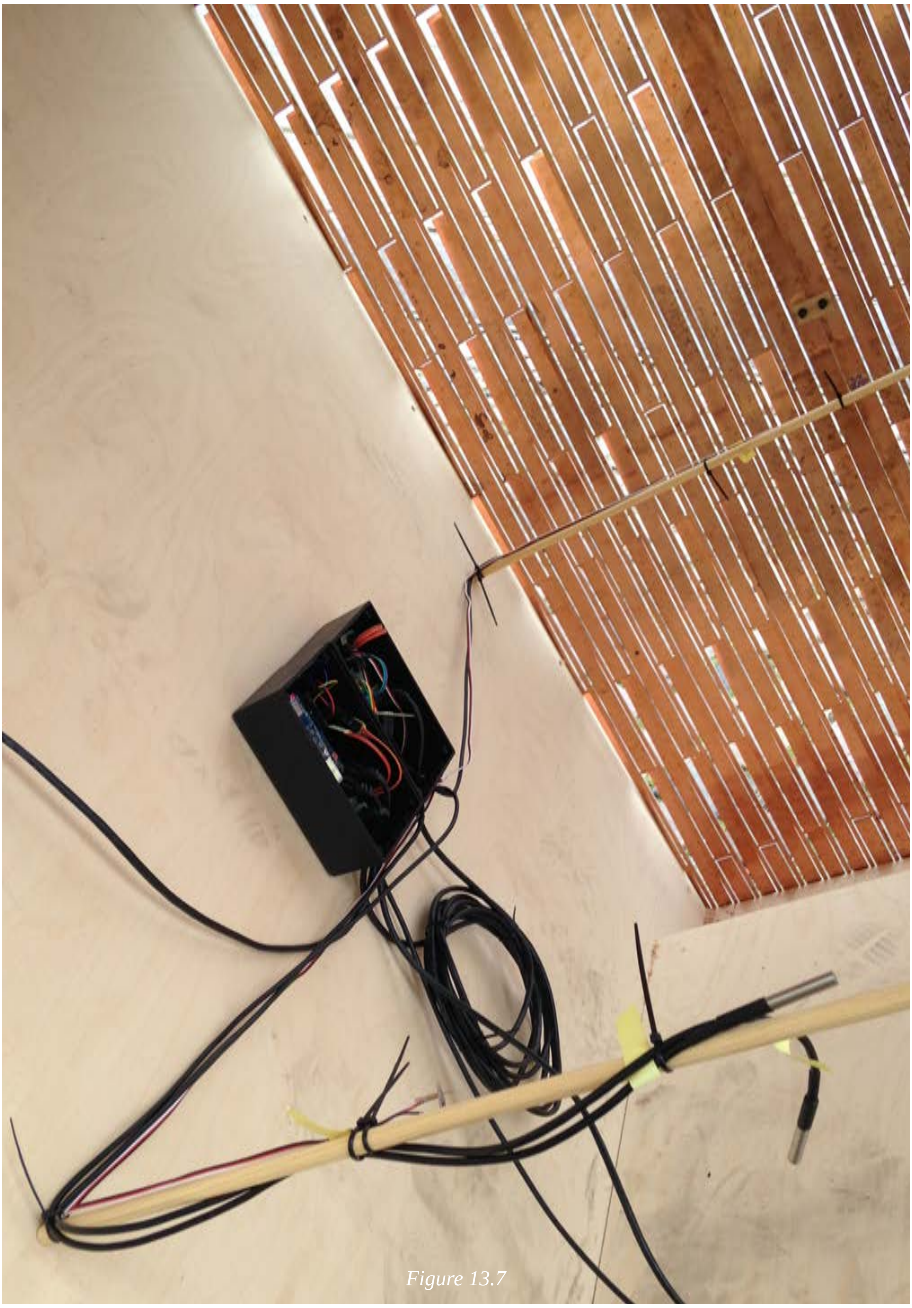


Figure 13.7

Sensors and microprocessor installed for post-construct analysis just inside the membrane and in the back of the space. The prototype consists of 24 panels with the dimensions 490x1490mm. Six clusters of four panels are organised with different milling patterns and orientations. Three clusters are spatially 'enclosed', with a single cluster being framed further by the external screen (see figure 13.5). Photo by Isak Worre Foged.

proposed method and model, additional layers influencing the properties are proposed simply by adding the acrylic layer. This modifies the microclimatic environment of the composites and thus the subsequent modification of the thermal environment for humans. To extend such studies, more advanced modes of acting layers could be integrated, thereby merging several behavioural layers to increase the ability to function in relation to other input values besides that of temperature.

The additive principles discussed within the theoretical chapters of the thesis are extended in this study by subtractive processes. The combination of these processes appears to offer another level of design instrumentality, given that a method and model of additive principles alone logically will expand continuously in space. Within this study, the additive and subtractive processes are integrated on two levels: firstly, by the aforementioned molecular transformative processes of the copper surface, as discussed in chapter 4, Tectonics; and, secondly, by the design process of adding and subtracting layers of the isotropic composites. The capacity of progressive additive and subtractive processes may signify a greater potential for responsive models geared towards adaptive models in architecture, as defined in chapter 5, Computation. This in turn reaches for the theoretically described architectural epigenetic model, a hybrid of Darwinian and Bernard Machines, by combining evolutionary design processes and environmentally induced transformative processes into one evolutionary architectural model.

The aspects and potentials identified and discussed above could be the starting point of new design experiments beyond this thesis in a move towards an expanded design methodology for Environmental Tectonics in architecture.

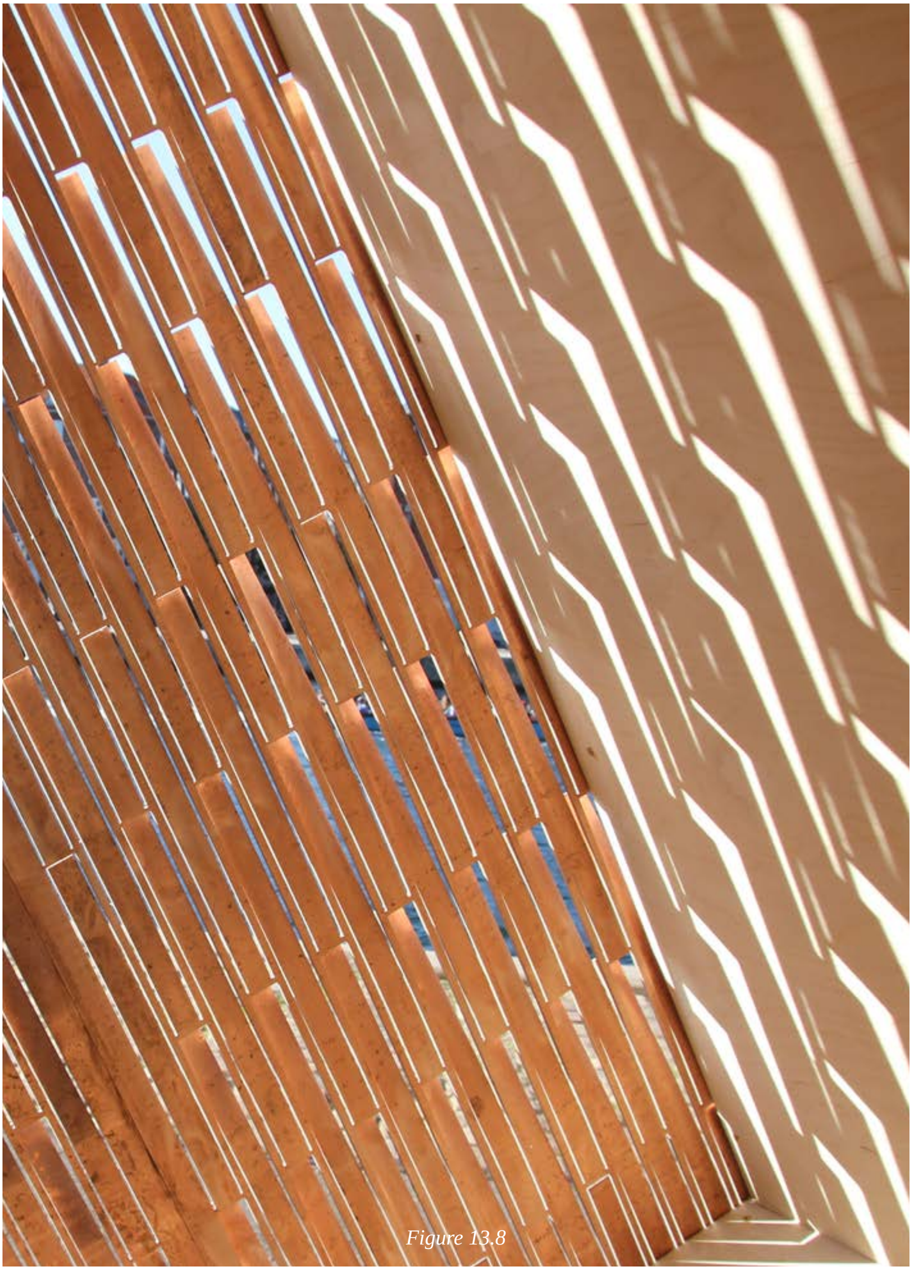


Figure 13.8

Sunlight patterns on the inner side of the envelope as a dynamic environmental articulation based on the responsive elements. Photo by Isak Worre Foged.

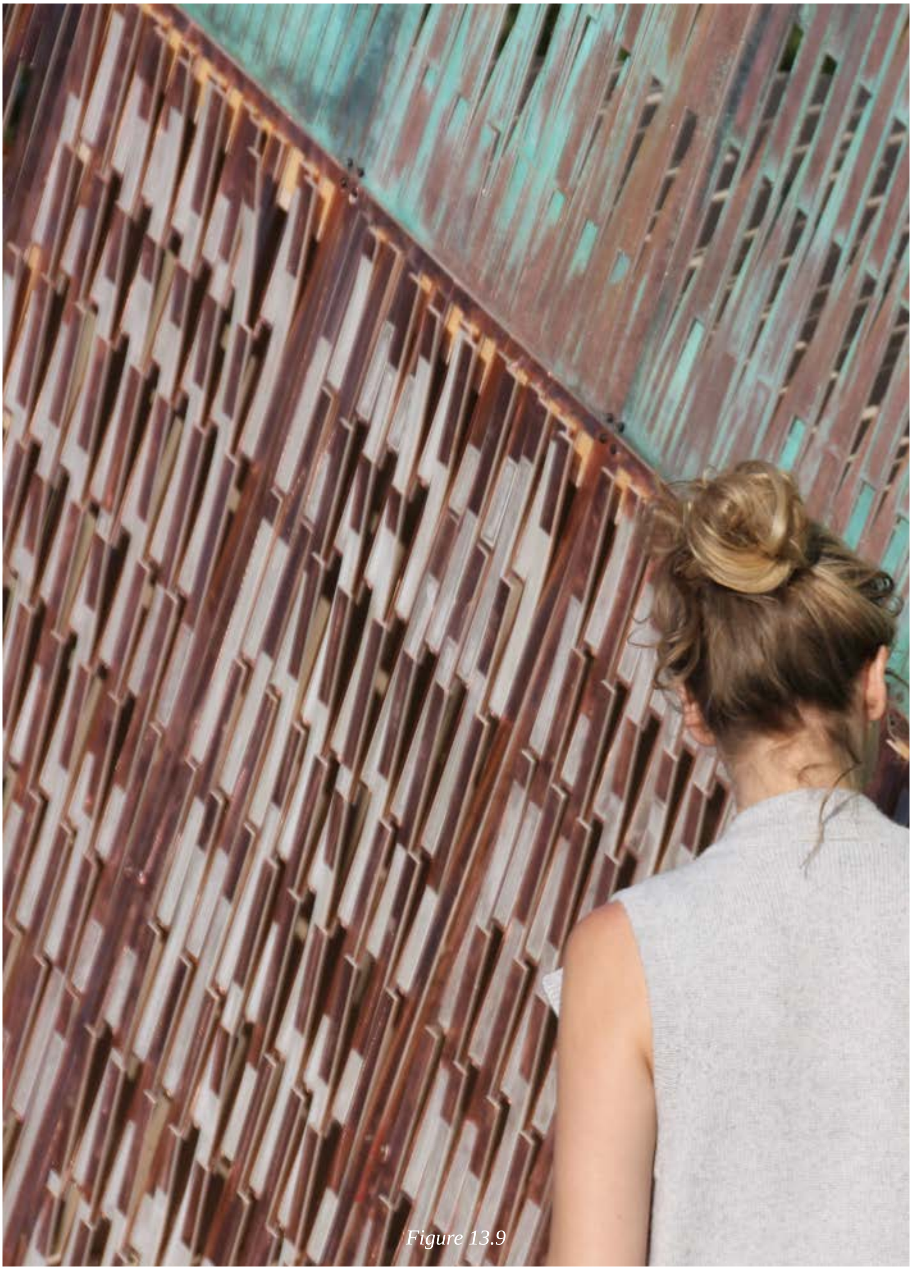


Figure 13.9

Full-scale prototype, measuring approximately three by eight meters as installed next to the Danish Architecture Centre, Copenhagen, for two months, for demonstration, measuring and observation. The image illustrates the articulation of the composite and its resultant bending behaviour. Photo by Isak Worre Foged.

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14

Synthesis

14.0 Preliminary

This chapter serves to synthesise the theoretical propositions in Fields (part 2, chapter 3 to 6) and the experimental design work and findings in Probes (part 3, chapter 7 to 13) with current associated strands in architecture and architectural research not discussed earlier in this thesis. Hence, the intent is to further elaborate upon and position the research, after the theory building and the experimental work, and to mark the research boundaries with greater intelligibility. By elaborating the boundaries drawn by the delineation in the thesis, a starting point for further studies beyond this research may become clearer. Finally, the chapter is used as an additional basis for the concluding remarks and the proposed thesis contributions in the following chapter.

14.1 Research field associations

In the thesis parts Foundation, Fields and Probes, different state-of-the-art approaches to environmentally sustainable architecture were discussed. From these discussions and arguments, relationships and differences to architectural design approaches were suggested, including associations with concepts of Free-Running Buildings and Performance-Oriented Architecture. Also, from a theoretical perspective on environmental constructions, notions of environmental perception, matter organisation and immaterial constructions were discussed. The connections to these parallel research efforts are further elaborated upon below.

Performance

The aforementioned basis for a performance-oriented and performance-based architectural approach is the capacity to connect representational geometric modelling and environmental simulations in a feedback loop (Hensel 2013; Malkawi 2005; Turrin 2014). As has been discussed, explored and applied by experimentation, such connections between a form and its environment are also explicitly part of an instrumental method for Environmental Tectonics. Yasha Grobman et al examine the architectural methodology of feedback between an environmental simulation and a generative model (Grobman et al. 2009; Grobman et al. 2010). They conclude from these studies that performance models must be developed according to specified design tasks. Hence, architectural performance as a methodology is, from this perspective, also the adaptability of the performance method to a design project. This statement aligns with conclusions on general architectural design processes, in which Lawson states that the most important task of the designer is to recognise and apply the right design method and design process (Lawson 2006). These statements may be seen to be in opposition to the proposed design methodology of Element, System, Formation, as based on the examination of tectonic architecture in chapter 4. However, the proposed design system is not intended as a restrictive design model. Rather, by its non-formal attributes and its three levels, all open to outer and inner

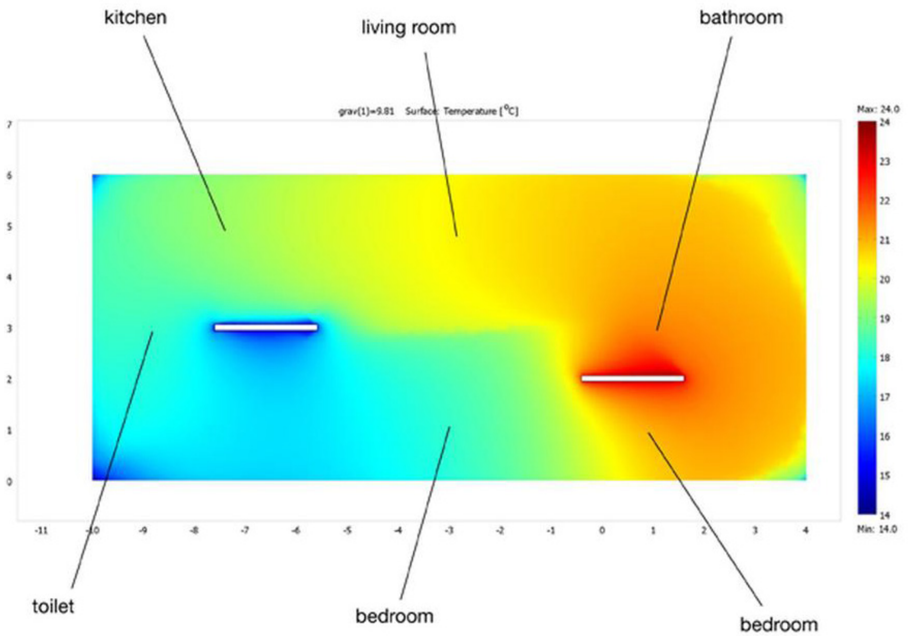

Figure 14.1

Interior Gulf Stream project by Philippe Rahm Architects. The space programme is defined by the temperature gradients, but indicates a neutral or non-integrated boundary condition to the outer environment along the edge of the space definition.

influencing factors, the design model is argued to be an open design system oriented towards Environmental Tectonics in architecture. The extended design model, beyond the environmental performance feedback loop, may clarify an additional distinction between the above performance approaches and an Environmental Tectonics approach. Performance, from this perspective, becomes the application and adaptability of the Element, Systems, Formation design model itself, and the connection of a behavioural model and its pairing with the environmental simulated model of human sensations.

The approach of Free-Running Buildings is, in fact, the vernacular approach of many buildings' ability to, for instance, open windows and apply and operate window blinds by human actions (Nicol & Humphreys 2010). From this the Adaptive Thermal Method is derived, basing perceived thermal comfort on the behavioural and physiological regulatory mechanisms of the human. The direct link between environment and human is in clear association with an Environmental Tectonic approach. By integrating human characteristics, it establishes a more complex relationship of human comfort than what is considered in assessing a thermal environment through the Predicted Percentage Dissatisfied method, as discussed in chapter 3, Environments. In spite of this relationship, the intents of Free-Running Buildings and Environmental Tectonics are different. Whereas the former is the method of assessing thermal comfort by human actions, the latter is the construction of environments that induce perceived sensations to effect an increasing integration of architectural aesthetics in environmentally sustainable architecture. Environmental Tectonics positions the responsibility for thermal sensations on both the human and the architecture. This points back to the arguments of a conceptual and applied approach that operates in an explicit relationship between the climatic environment, the architecture and the human. Further, as has been suggested, these three may form into inseparable entities because of their interwoven and reciprocal relationship.

Environmental Construction

This form of inherent connectivity between the human, the environment and the building has been theoretically discussed within this thesis by reference to architectural theoretician Jonathan Hill, Lisa Heschong and architectural scholar Michelle Addington, among others. Previously, applied architecture within this discussion has been shown by French architect and writer Philippe Rahm (Clement & Rahm 2006). Rahm explores in his work the relationship between humans and weather, or what he calls *Meteorological Architecture*. By stating an explicit relationship between architecture and aspects such as respiration and breathing, and citing convection and conduction as new tools in architecture (Rahm 2014), he investigates obvious architectural factors related to this thesis. The different and potentially problematic approach, in relation to the objective of Environmental Tectonics, is the way in which the architectural position appears to remain within a Modernist agenda, effectively reducing the potential of his ideas to the design framework of Modernism. Architectural scholars Christopher Height, Michael Hensel and Achim Menges stated, in relation to this argument:

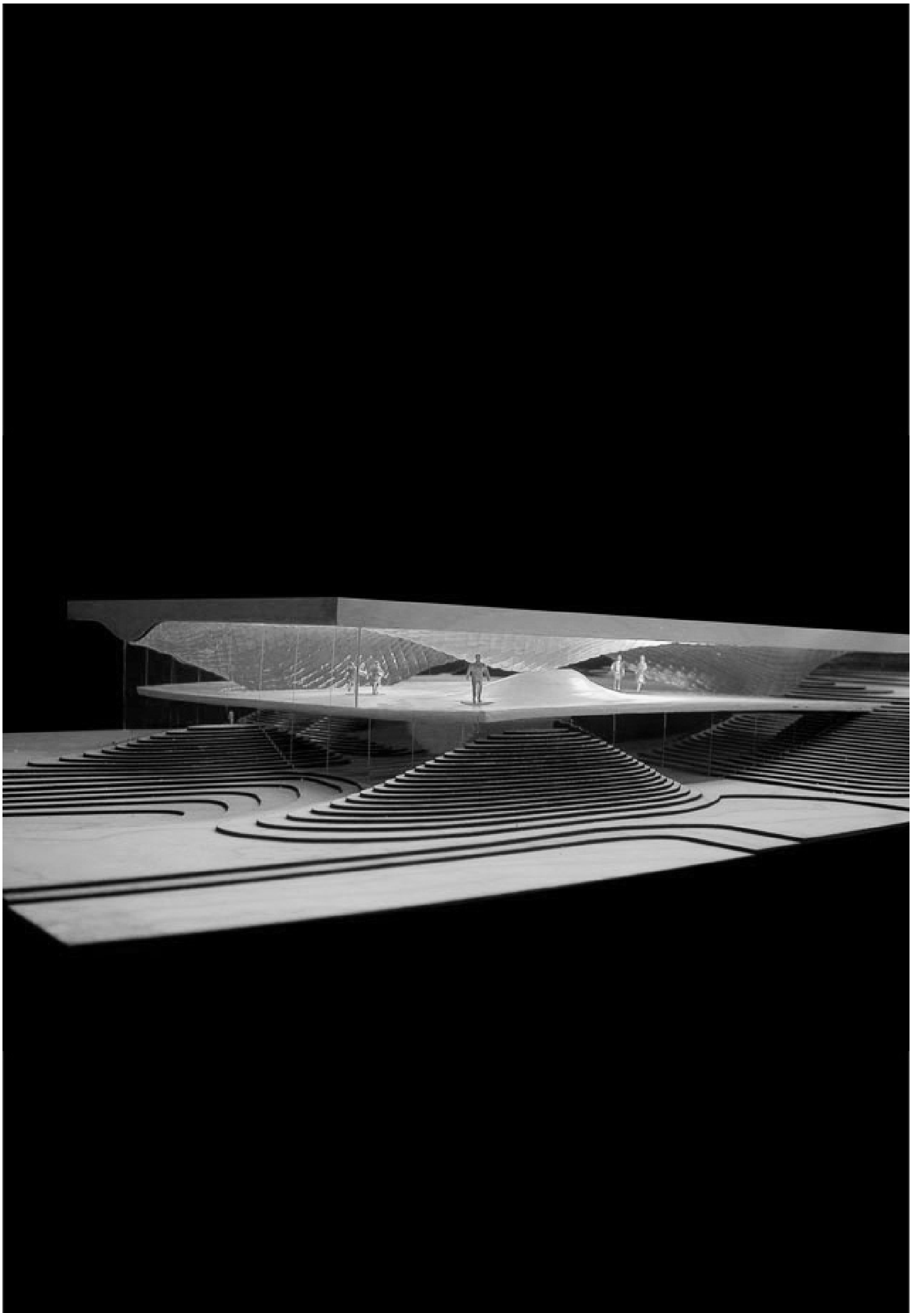

Figure 14.2

SIM Residence project (2006) by Sean Lally illustrates the undulating and permeable roof structure, but also the visually open glass facade and the resulting flux of solar energy and complexity of boundary conditions. Photo by Sean Lally/WEATHERS.

> *As a result, we often find these discourses reverting to a neo-modern Functionalism coupled to a Minimalist architectural formalism, such as is found in the work of Philippe Rahm, where environmental conditions are claimed to produce direct subjective responses in a quasi-behaviourist fashion. (Height et al. 2009)*

In the project *Digestible Gulf Stream*, heat sources are used to define the spatial programme. As is shown in the plan drawing, two-dimensional environmental gradients are created. But they do not interact with the conditions of the boundaries of the space, and therefore it illustrates a form of contained and isolated condition, rather than an open and environmentally interchanging architecture. This approach to an environmental architecture is also visible in the *Archimedes House* and the *Interior Gulf Stream* projects [Fig. 14.1], demarcating a clear and fixed boundary between inner and outer environment creation. Also, while Rahm considers human-based respiration, the environments simulated by Rahm do not show any indication of a direct interaction with or articulation of the relationship between human thermal sensations and buildings beyond the position of the person in the climatised spaces proposed.

In this way, it appears as if the approach does not integrate the transfer and transformation occurring near the architectural envelope and its potential articulation through such processes. While some of Rahm's projects engage with the building, becoming natural ventilation units themselves, as in the projects *Airflux* and *Windtrap*, by modifying the openings and spatial organisation to enhance particular air velocities in specific regions of the building, these projects seem, in a similar way, to be otherwise isolated from the environment surrounding the buildings. This approach, as a counter argument, may, however, enhance the inlet/outlet of air and thus increase the environmental flux through smaller openings in the building envelope, rather than considering the entire spatial enclosure as permeable and interactive. Such an approach may indeed become adequate in urban contexts with highly different microclimatic contexts, such as part of the building facing a polluted environment, while another part faces non-polluted conditions. Nevertheless, the problem of assuming climatic specificity and stability for architecture becomes clear through these projects, as the spatial layout depends on a constant air direction and air velocity to create the inner environments. When the local climate differs, the architecture will lose its means for relating the building to the humans and the surrounding climate.

Architect Sean Lally promotes, in this way, the construction of environments through the 'active context' (Lally 2007:28), which is not divided by a fixed boundary. Rather, Lally speaks of territories that are defined by light and temperature, as in the *SIM Residence* project [Fig. 14.2], where spatial articulation is determined by the thermal environmental articulation. The definition of the roof is based on the thermal territories it creates beneath it, with the vertical walls created in glass to ensure visual connectivity to the surroundings. While the roof form and its perforations are designed in relation to an outer and inner environment articulation, the rest of the building appears to be non-attentive to this intent. While interesting as an idea, the environmental conditions created by the roof design are projected down on the floor

Figure 14.3

An example of an Environmental Tectonic joint (Thermal Tectonics V) by the interrelated composite materials behaviour based on the thermal environment. Photo by Isak Worre Foged.

surface without considering the energetic flux provided by the glass walls. Hence, the project adopts the idea of glass as fixed boundary making, despite the initial intent of integrating latent and dynamic energies in the creation of the architecture. While an intention of energy as an articulating driver for architecture is obvious, the project indicates an approach that only partially considers the integration of environmental agency and does not explicitly relate this activity to the human and the sensations discussed previously.

Rahm's thoughts and his application of environmental articulation in relation to human physiological processes and Lally's ideas of energy territories are interesting approaches to an environmentally based architecture and align with parts of the arguments formulated in this thesis. In spite of this, differences from the approaches proposed here are readily identified when considering Environmental Tectonics' theoretical and instrumental grounding in the four causes of materialis, formalis, finalis and efficiens as elaborated upon in earlier chapters. While both architects' work indicates a causal relation between the final form and its effects on humans based on environmental constructions, it is more difficult to identify how the architecture is created by formation and what the material causalities are in relation to environmental sensations for humans.

Tectonic Dimensions

From the perspective of the four causes as a measure for environmental constructions, as discussed in the previous cases in chapter 3 to 6, and the results of the design experiments, chapter 7 to 13, it has been attempted to indicate differences between current associated approaches and Environmental Tectonics. This, in particular, is argued by the notion and use of matter, rather than material, which positions the understanding of an architecture as a process of constant appearance enabled by and for the reason of human sensation. It is in a philosophical as well as a practical and applied perspective that the dynamic revealing through the articulated organisation of matter and exergetic capacities unfolds the Environmental Tectonic potential.

This statement also attempts to reposition the notion of the tectonic joint as a defining measure for tectonic architecture (Frascari 1984; Frampton 2001; Semper 2004) by suggesting that the tectonic joint become the continuously articulated materialisation of joining matter and energies towards the revealing of environmental forces. An example of such environmental tectonic joining could be the articulation of composite layers within the design experiment Thermal Tectonics V (chapter 13). Here, the ongoing formation is based on the continuing material and environmental force relationships, which cause the immediate making of the thermal and visibly perceived environment [Fig. 14.3].

Another, more subtle example of an Environmental Tectonic joint is the mortar connection in the Thermal Tectonics II study (chapter 10). Here, the colouration of the mortar follows the bricks, but by the vertical lifting and small horizontal overlay, it allows the flow of air through the envelope and a change in absorbed solar radiation. Colour, lifting and overlay are determined by the relationship between solid matter

Figure 14.4

The binding mortar within the Thermal Tectonics IV probe illustrates a joining of materials and thermal environmental aspects that cannot be considered in isolation. Photo by Henrik Christensen.

properties, element geometry, fluid mortar drying time and strength, the outer climatic environment as gaseous matter and the inner perceived environment [Fig. 14.4].

The suggested approach thus indicates potential in the reciprocal interrelations between what is understood as climate and architecture at different scales of the architectural domain, from the overall envelope to the material properties joining in matter organisations. The organisation of matter, is thus not bound to the visual aspects, but an organisation of everything that influence the human senses. Such aspects of Environmental Tectonic joints indicate a distinction from the associated approaches and attempt in turn to clarify both the similar and dissimilar aspects to environmental constructions in architecture. From these arguments, and the previous discussions, it may be reasonable to propose an extension of the four causes, originally formulated by Aristotle and related to tectonics by Heidegger, in relation to Environmental Tectonics. While Heidegger elucidated how the architect as a making agent is directly related to the unfolding of the four causes, it can be suggested that the agency is a causality in itself when psychological and physiological aspects become integrated into the making of environmental constructs defined by the human behaviours. This is visible in the psychological aspects of environmental perceptions, as formulated by Uexküll, Hawkins, and Nicol and Humphrey, and in physiological aspects of environmental making by human behavioural activities such as choices of clothing and physical activity. The causality of and by human activities, causa humanus, is, from this perspective, indicative of an equal footing with the other four causes in the making of Environmental Tectonics in architecture [Fig. 14.5].

14.2 Research field boundaries

The thesis, grounded in three theoretical fields of Environmental Architecture, Tectonics in Architecture and Computational Architecture, is developed from a broad architectural platform. In attempting to delineate the work and construct a comprehensive yet distinctive framework, boundaries have been created against fields that could have had greater integration and influence on the research. The three fields of Cybernetics, Biological Systems Theory and Environmental Psychology are all knowledge fields that strongly relate to this thesis. While they have all informed the research, they have largely been secluded within the dissertation document so as to not shift attention to the primary three fields elaborated upon in part 2 and applied in part 3. To elaborate upon their partial omission of the principle research, each field is briefly discussed below.

Cybernetics

As stated by the Oxford English Dictionary, cybernetics is *'the science of communications and automatic control systems in both machines and living things'* (OED, 2014). This positions dynamic feedback mechanisms at the core of cybernetic theory and applied cybernetic models. The relationship to the construct

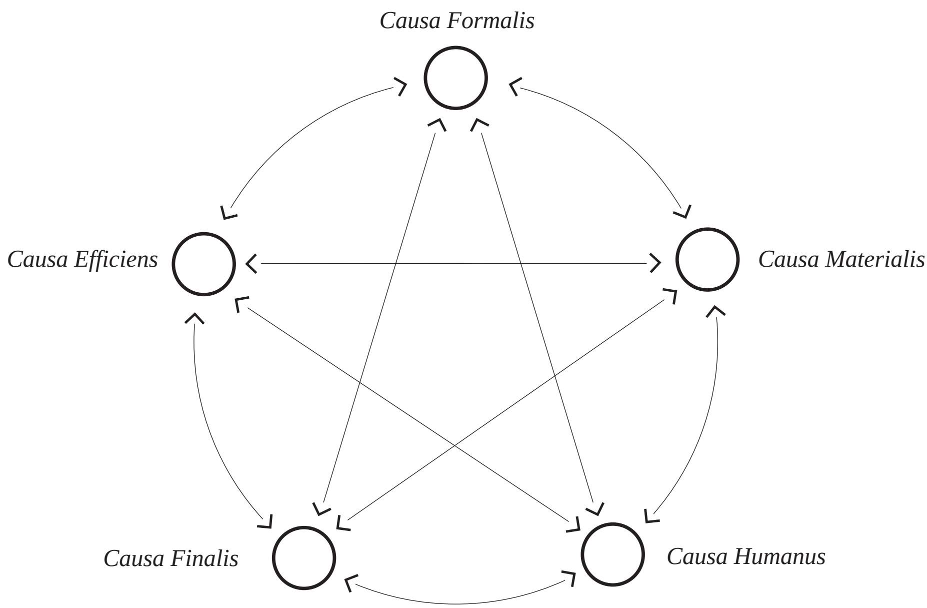

Figure 14.5

The proposed five causalities that define Environmental Tectonics as an architectural approach to a human-oriented environmentally sustainable architecture. Diagram by Isak Worre Foged.

of environments becomes clear when recalling Uexküell's Funktionskreis, between acting agents, that by their perception creates a unique environment. Feedback is also of central concern to the Performance-Oriented approach in architecture, and in the proposed Environmental Tectonics framework. Gordon Pask, a British cybernetician, wrote the introduction chapter to the aforementioned *An Evolutionary Architecture* by John Frazer, a forerunner for the integration of evolutionary processes in architecture. Also mentioned earlier is the relationship between material dynamics integration and responsive systems with reference to developments in robotic science. While the material agency of these models is guided by material characteristics currently studied in architecture, the control systems of material models are typically supported by cybernetic information theory on response patterns in artificial intelligence models (Brownlee 2011). Cybernetician William Ross Ashby (Ashby 1956), Heinz von Foerster (Foerster 2003) and Ranulph Glandville (Glanville 2004) are figures who have developed, described and applied such cognitive and cybernetic ideas. Currently, control system processes, towards embodied artificial intelligence models are, for instance, handled and evolved by adaptive responsive systems (Ayres 2008; Ayres 2011) and homeostatic (Cariani 2009; Foged & Poulsen 2010) evolutionary processes in relation to architectural models. In the last design experiment, described in chapter 13, it was discussed how a responsive system might be advanced by the addition of several acting layers. From a cybernetic perspective, such layers could be nested, not only as matter organisations but also as metaphysical logical behavioural systems, by calibrating the responsive behaviour through an embedded adaptive mechanism.

Biological Systems Theory

Beyond the design approach of Biomimicry, borrowing functional innovations in nature and applying them in architecture, is the examination of the systemic relationships between biological and ecological processes. Such processes are systems that unfold across scales of magnitude. These aspects are addressed in architecture primarily by the extensive authorship on the subject by Michael Hensel (Hensel et al. 2010; Hensel 2006a; Hensel 2010; Hensel 2006b). Hensel advised a greater investigation into the complex relationships in ecologies that affect the scale of architecture, discussing different forms of equilibrium systems for the sustaining of the climatic environment as we know it. While notions of evolutionary processes, as related to progressive architectural models, have been discussed throughout the thesis, it has not included the systemic organisation of biological systems as ecologies that form in relation to large-scale mechanisms with an impact from the macroclimate to the microclimate. This is an intended demarcation to maintain focus on the scale directly related to humans. Nevertheless, towards an extended understanding of the flow of energies and matter, as related to Environmental Tectonics, an extended integration of contextual ecosystem processes may lead to new insights and new relevant questions. Of immediate interest could be the application of the Element, System, Formation method to larger scales, examining the potential effects of energy and information transfer between architectures. Such studies would be in direct relationship with the concept of *Industrial Ecology* (Hepbasli 2012; Hensel 2012). From this, Herbert Simon's systems boundary of an inner and an outer environment would simply be repositioned so as to understand the urban system as an inner environment, with the regional context as the outer condition. A more profound systemic organisation of matter and energy might also lead to a more operational definition of how to organise and articulate the inner/outer boundary making within an Environmental Tectonic approach.

Environmental Psychology

Central to the thesis are the human experience of architecture and the sensations caused in humans by architecture. Specifically, audible, tactile and visible aspects have been included in the suggested evolutionary design processes. This means reading and understanding the environment surrounding humans. As one of various starting points for this thesis, humans' psychological and physiological relation to the environment was discussed with specific reference to Ulrich (Ulrich 1984), Hawkins (Hawkins & Blakeslee 2004) and Fich (Fich 2014). Such relationships are described as Environmental Psychology, which attempts to understand the active relationships and the affects they may have. This, again, points back to Uexküll's theories of environmental perception by the sensing human. Uexküll influenced the later work of James Gibson (Pol 2006), who worked on defining the relationship that he termed 'affordances' (Gibson 1979). Gibson stated:

> *I have described the environment as surfaces that separate substances from the medium in which the animals live. But I have also described what the environment affords animals, mentioning terrain, shelters, water, fire, objects, tools, other animals, and human displays. How do we go from surfaces to affordances? (Gibson 1979:127)*

The discourse of understanding an environment of affordances, rather than surfaces, is in clear relationship with an Environmental Tectonics approach, where acting relationships of matter and a perceived environment construct affordances in the appearance of architecture. Towards an extended elaboration of Environmental Tectonics beyond this thesis, Gibson's concepts of environments, as well as his immediate relationship to Uexküll et al, may afford new insights into constructing new architectural environments.

Described in brief, the above three fields indicate potential for further research related to this thesis and advancement of the application of the suggested five causalities towards further applications of an Environmental Tectonic approach in architecture. The added three fields' relevance to further studies in environmental architecture is also considered elevated as the theoretical concepts overlap in both theory and operational models in their relationship to the organisation and perception of an environment for humans.

15

Conclusions

15.0 Preliminary

This chapter intends to present the concluding remarks of the thesis. It includes a revisit of the project beginnings by pointing back to the initial problems and the objective formulated in the thesis Introduction. The revisit is also the starting point of a short thesis summary, including the Synthesis of the previous chapter. This in turn permits the final propositions for an Environmental Tectonic approach to be formulated based on the theoretical and experimental findings. With these framed, the research questions can be answered. Based on these sections, the formulations of the core research contributions are listed and a last brief conclusion is offered. Finally, as a last discussion, reflections on results and research methods and potential future studies are discussed.

15.1 Revisiting from the beginning

Within the wider scope of the initial problems described in the thesis Introduction, relating to architecture broadly and environmental architecture particularly, it was indicated that both a theoretical approach and a series of specific applied methods could support an agenda for human-oriented environmental sustainable architecture. The listed initial problems included questions on humans' influence on the climatic environment, humans' environmental sensations and architectural design methodologies. It was evident that humans, through architecture, exert a significant impact on the natural environment through the use of damaging energy sources. The primary response and architectural application to address this problem has been based on refinement of mechanical constructs paired with an increasing isolation of humans in sealed buildings. This approach has decreased the loss of energy through containment of heat, but it has also decreased the relationship between humans and the local environment and buildings and the local environment. Hence, it was less clear how architecture could construct environments for humans that increased the understanding of and relationship to a given context, while also attempting to decrease the use of climate-damaging energy sources. This situation provided the grounds for the problem statement.

The objective of the research project thus became the formulation of a theoretical and instrumental framework for an human-oriented environmental architecture. To address the aspects of human-based environmental perception and its possible constructions, the fields of Environments, Tectonics and Computation were outlined and discussed.

In the chapter on Environments (chapter 3), it was examined how environments can be perceived and made instrumental in early architectural design processes. The discussion introduced four methods of environmental construction and the relationship between the organisation of matter and the articulation of aesthetics. The applications of these aspects were discussed through a set of acoustic simulation methods and two primary thermal simulation methods, namely the adaptive thermal model and Fanger's comfort model. The latter was, to a greater extent, elaborated and applied as the basis for an architectural method for early design phases towards developing architecture in relation to thermal sensations.

In the chapter on Tectonics (chapter 4), it was discussed how construction methods can be based on the notions of appearance through discernible design steps by reference to Semperian Stoffwechsel. This concept was related to the four causes reintroduced by Heidegger from Greek philosophy, which in turn was argued to be the measure of tectonic articulation in architecture, and therefore these notions became the basis for Environmental Tectonics. The chapter also introduced the design system - Element, System, Formation - as an open, scalable method related to additive and transformative processes. Addition and Transformation, also related to Stoffwechsel, were discussed as a means to integrate concepts of environment and construction into an instrumental process of appearance, the intent of the interrelated four causes. This was argued to affect the perception of environments and the articulation of architectural aesthetics. Lastly, the chapter discussed the Membrane as an envelope to be the central concern of an Environmental Tectonic approach.

In the chapter on Computation (chapter 5), the growing field of architectural computational processes was delineated into concepts based on evolution as a derivative of the discussions and propositions of the two previous chapters. The principles of progressive steps by environmental influence were discussed from generative and genetic algorithmic perspectives and how these can be applied to architectural design processes. These notions enabled the discussion and argument for an architectural epigenetic model, originally formulated as a biological model by Waddington, which integrates human and environmental influence in both design and constructed realms. Evolutionary models allow open and loosely defined search procedures geared towards potential solutions, as favoured in early architectural design processes. Furthermore, with reference to parallelism, it was suggested how these processes exhibit computational procedures that can be applied as material and machine-based, layered and interacting, responsive and adaptive methods and models in architecture.

By correlating (chapter 6) insights within the three fields based on case studies and literary studies, three primary terms were identified for an Environmental Tectonics approach to environmentally sustainable architecture. These defined, in brief, the notion of Aesthetics by environmental constructions, Organisations by decomposable yet non-discrete systems, and Evolution by discernible progressive steps. These three aspects are in turn congruent to the four causes.

Probes (part 3) of the thesis explored and advanced the concepts discussed in Fields (part 2) by focusing on a gradual development and integration of evolutionary processes and environmental sensation assessment throughout the seven individual design research experiments (chapter 7 to 13), which acted as digital and analogue probes. The experimental findings in part 3 are laid out below as an advancement of the theoretical proposition from part 2.

Based on the experimental design studies, a final Synthesis (chapter 14) of the research work was presented. Here, the similarities and differences among associated approaches to environmentally sustainable architecture were discussed. This in turn allowed the clarification of the research field boundaries, pointing to Cybernetics, Biological Systems Theory and Environmental Psychology as theoretical fields that could influence future research directions towards an advancement of Environmental Tectonics as formulated here.

Based on the theoretical and experimental studies, an extended elaboration of Environmental Tectonics was presented by extending the four causalities to five causalities. This was followed by an example of how the articulation of joints could be understood from an Environmental Tectonics perspective, which returned to the discussion of the present theories of tectonic architecture as elaborated in Tectonics (chapter 4) towards what Frampton posited as *'the poetics of construction'* (Frampton 1995).

15.2 Environmental Tectonics – An Architectural Framework

The objective of the thesis was to examine, identify and describe a theoretical and instrumental framework for a human-oriented environmental architecture. Its formulation was attempted through a series of propositions that were formed by the studies presented across the Introduction, Fields and Probes (part 1 to 3). To reiterate, this approach is taken to formulate a descriptive architectural approach for early design phases that is intended to be both adoptable and adaptable.

The propositions, developed from the three Fields (chapter 3 to 6), have been reassessed according to the experimental design studies (chapter 7 to 13) and the derived theoretical discussions. In total, they form the architectural framework.

Proposition 1:
Environmental Tectonics is a matter-based architectural practice.

The proposition suggests the idea of architecture as constructed by gaseous, fluid and solid phases of matter and by the ability to change from one state to another in the manifestation of architecture. It promotes the understanding and instrumentality of architecture as a process in constant articulation, and architecture as the merging of solid constructions and fluid and gaseous constructions commonly understood as space.

This proposition and its argument are based on the case studies in Fields (part 2), with particular reference to the Blur Building by Diller/Scofidio+Renfro, The Royal Theater by Lundgaard & Tranberg and the MediaTIQ by Cloud9. A further indication of the transformation processes was identified in copper and sandstone (chapter 4). These examples show how architectural constructions can be articulated and how they are articulated by changing organisations of matter and the direct effect on humans. The proposition binds the environment and the visually perceived matter together, as argued and exemplified by the examples in Tectonics (chapter 4). Within the design experiments, the notion of instrumental matter is expanded to the human being, who by behaviour modifies the microclimatic environment directly through evaporation, respiration, clothing and activity and indirectly through the thermal perception relationships comprised of the thermal sensation equations as based on the six factors described in Environments (chapter 3) and in the design research experiments Thermal Tectonics II to V (chapters 10 to 13).

Proposition 2:
Environmental Tectonics is architectural aesthetics expressed by the organisation of matter.

When the aesthetic dimensions are based on the way we perceive the world, which is derived in part from Greek philosophy, as discussed in Environments (chapter 3), Tectonics (chapter 4), and Synthesis (chapter 14), then the organisation of matter is directly connected to the aesthetic articulation in architecture. Hence, it suggests a repositioning of the predominant notion of aesthetics, from a visually described dimension in architecture to a multi-sensorial prescription made instrumental by the organisation of matter. In Environments (chapter 3), the Therme Vals by Zumthor, the Roman Baths and the Nordic Pavilion by Fehn exemplify how architecture can enhance the aesthetic dimension through articulated sensations. The increasing sensation caused by architecture was explored throughout Probes (part 3), in which design research models simulated variation on an environmental condition to enhance sensations. Such conditions were particularly evident in the studies Acoustic Tectonics I and II (chapters 7 and 8), as the effect of sound has an immediate impact on the sensing of the architectural construct, whereas thermal sensations are both perceived immediately and delayed, as shown in Thermal Tectonics II to V (chapters 10 to 13).

The two propositions suggest, firstly, an instrumental agenda, the organisation of matter in bounded and unbounded modes. Secondly, instead of pointing directly to energy efficiency as an aim, they point to the construction of environments and the derived aesthetics, which subsequently indicates improvements to the current energy imbalances in the built fabric. The latter statement is related to the findings in Free-Running Buildings that aim to reduce the use of fossil fuel-based energy by decreasing the difference between thermal comfort and external temperatures based on human adaptation, thereby decreasing the necessity to cool or warm spaces mechanically.

Proposition 3:
Environmental Tectonics is determined by five causalities.

Environmental Tectonics is not an architecture of reference or of autonomy. It is an architecture defined by the five interrelated causalities inherent in the Heideggerian (Heidegger 1977) notion of techné towards poeises and its extension of the human as an acting causality. The five causes are the causality of matter, causa materialis, the causality of a forms formations, causa formalis, the causality of the final form, causa finalis, the causality on effects on humans, causa efficiens, and the proposed added causality by humans, causa humanus.

The proposition is based on the theoretical studies related to Heidegger, Aristotelian philosophy and the general grounding of architectural tectonics in techné by Semper (Semper 2004), Frampton (Frampton 1995), Frascari (Frascari 1984), Sekler (Sekler 1965), Hartoonian (Hartoonian 1994) and Beim (Beim 2004). As an example, the four initial causes are investigated in Tectonics (chapter 4) and applied through Probes (part 3) by the Element, System, Formation methods combined with evolutionary processes and human-environmental causalities by computational simulations. In addition, causa materialis, from proposition 1, is to be understood as the causal relations of matter, hence a merged material and environment description.

Proposition 4:
Environmental Tectonic architectures are Maximum Structures.

The architectural approach integrates a compound of aspects and forces indicating a concept of maximum structures. When gravity is a tectonic focal point, the articulation of structures leans towards minimum structures based on structural efficiency and its related expression. Thus, Environmental Tectonics aims, in contrast, to capture the inclusive yet environmentally distinctive articulation so as to relate architecture and context. In turn, the ontology of tectonic architecture can be argued to be repositioned in this thesis.

This statement and proposition are derived from the above proposition of multiple causalities acting to form a human-environmental-oriented architecture. This argument is supported by the design experiment, particularly in the study Thermal Tectonics II and Thermal Tectonics III (chapters 10 and 11) where the different and opposing factors influence the progressive design process towards a plateau of solutions, rather than a singular summit. This condition is further evident if the architect introduces search ‘guides’ to, for example, formal desires by influencing the search process in a particular direction. Such restrictions were applied in the studies Acoustic Tectonics I and Acoustic Tectonics II (chapters 7 and 8) to follow site requirements with no direct relation to the sound-based description otherwise informing the design progression.

Proposition 5:
Environmental Tectonics applies Semperian Stoffwechsel.

The proposed approach relies on the notion of Semperian Stoffwechsel, which emphasises the discernibility of a composite architecture through its transformative processes at all times of design evolution. Thus, a design’s process of appearance at any point in time determines Environmental Tectonics. Such processes are asserted to increase the relationship among the above five causes.

This argument is stated in parallel to these five causes, as they interact with appearance in architecture through discernible steps. The gradually perceivable modification was elaborated in relation to evolutionary design models and evolutionary computational models, as discussed in Computation (chapter 5). Rather than an automated optimisation procedure, evolution was identified, from philosophical and applied perspectives, as an approach to connect Stoffwechsel with environmental assessment oriented towards the making of human-oriented environmental architecture. This theoretical and applied approach was shown in Probes (part 3, with the exception of Thermal Tectonics I (chapter 7)). Different levels of design instrumentality were shown in the design experiments, specifically through a dynamic interaction with the occupier perspective in Acoustic Tectonics II (chapter 8), from the designer's perspective in Thermal Tectonics II (chapter 10), and from the dynamic interaction of responsive matter organisations in Thermal Tectonics IV and V (chapters 12 and 13).

Proposition 6:
Environmental Tectonics has multiple authors.

Environmental Tectonics acknowledges the environment as a making agent. This allows the authorship of architecture to be situated across time and across multiple causalities. This enforces the dynamic, and potential unforeseen, environmental events occurring in the formation of architecture, rather than the intent to isolate architecture from its ongoing transformative potential. These processes are asserted to strengthen the relationships among the above five causes.

This argument is anchored in the associated theories of Ebeling (Ebeling 2010), Hill (Hill 2012), Leatherbarrow and Mostafavi (Leatherbarrow & Mostafavi 2005) and Hensel (Hensel 2013) as discussed in Environments and Tectonics (chapter 3 and 4). By integrating matter agencies (material and environment) into the causality of architectural formations, its final form, and its effects, as shown in the design experiments and in particular in Thermal Tectonics II to V (chapters 10 to 13) the appearance of and by architecture is shown to be increased by an extended authorship.

Proposition 7:
Evolutionary processes instrumentally empower Environmental Tectonics.

Environmental Tectonics, as shown in the previous propositions, can advance its potential through multi-authored influenced evolutionary systems. First, this is argued to extend the capacity for processes of appearance by observable progression, relating to the above-mentioned Semperian Stoffwechsel and the five causalities. Second, it allows the explicit integration of environmental aspects under organisational processes, which was studied in the design experiments. Third, it supports the use of simple elements, a system and their phenotypic formations, as explored particularly in Thermal Tectonics I, II, IV and V (chapters 9, 10, 12 and 13). And, fourth, it makes use of parallel and distributed computational procedures, which extends both computational power and versatility of application, in particular when used as design approaches allowing combinations of evolutionary strands to be reconnected and 'mutated' by human agency, as discussed in Computation (chapter 5).

Proposition 8:
Epigenetic processes instrumentally advance Environmental Tectonics.

Environmental Tectonics, being based on evolutionary processes, can advance through a hybrid instrumentality of epigenetic processes extending the capacities of the Darwin/Mendel and Lamarck/Bernard mechanisms towards a more complete integrative model for continuous matter organisation in architecture. This is proposed to allow an extended search for time-based environmental constructs and thus an extended instrumentality for the on-going construction of human-perceived sensations.

This argument is based on the discussions of dynamic matter organisations in Environments and Tectonics (chapters 3 and 4) and their integration into evolutionary processes in Computation and Synthesis (chapters 5 and 14). Within the design experiments, these ideas were applied in Thermal Tectonics IV and V (chapters 12 and 13) by integrating dynamic responsive mechanisms into the organisation of behavioural architectures. The matter behavioural characteristics were related to the perceived environment and embodied into the evolutionary approach of proposition 7 above. Nonetheless, the capacity of the epigenetic model has yet to be explored extensively, as the applied research only integrates an early merging of evolutionary and environmental dynamics.

15.3 Answering and Restating Research Questions

Based on the research findings and the elaborated theoretical and experimental framework formulated above, conclusions can be stated in relation to the research questions formulated in the thesis Introduction (chapter 1).

How can environmental constructions enrich human-perceived environments? (Q1)

This question is central to the foundation of the studies in Environments and Tectonics (chapters 3 and 4) and as a basis for the experimental studies (chapters 7 to 13). In these chapters, it is argued that the explicit, non-discrete connection between an outer environment, a natural environment, an inner environment, architectural constructs and the human is central. This has been studied from a general theoretical perspective and in particular from applied perspectives related to audible, tactile and visual sensory perspectives. From the arguments enabling propositions 1 and 2, one answer is that human-perceived sensations are intensified by the articulated temporal organisations of matter. In turn, environmental constructions enrich human-perceived environments by the formations of temporal matter-based constructions towards extended architectural aesthetics.

(Q4) *How can analytical and numerical methods of human sensations of the environment be integrated into the architectural conceptual design phase?*

With the stated need to increase architecture's ability to construct relations between the environment and humans, the question asks for architectural methods that integrate such connections in early design phases. Without the application of advanced assessment of environmental sensations in early design phases, the computational evolutionary model does not have an environment to evolve within. Hence, the reason why becomes the inability to evolve an environmental architecture through computation without the environmental assessment. The complexity of determining environmental sensations, particularly in relation to thermal aspects, as discussed in Environments (chapter 3), promotes simple evaluation models that allow fast feedback to a design agent. However, to include a larger set of factors as instrumental design variables, it was discussed and illustrated how the relatively comprehensive model proposed by Fanger et al. can be integrated and made operational in conceptual design phases. This approach was thereafter illustrated in Probes (part 3). As argued in proposition 3, a broad set of factors is needed to engage and relate all five causalities, including human physiologically and behaviourally determined factors (clothing rate and metabolic rate) and climatically and architecturally determined environmental factors (ambient temperature, radiant temperature, humidity and air velocity). The integration of the thermal perceived sensations is, naturally, only one specific approach to answering the question, but it points to a general level required when integrating numerical methods towards a qualitative impact on humans.

(Q5) *How can the relation between a structure and an environment be understood for environmental constructions?*

This question relates to the second question, as it promotes the discussion of what aspect to integrate within advanced environmental architectural design models. However, it also relates to the fundamental discussion of architectural boundary-making. In Environments and Tectonics (chapters 3 and 4) it was discussed how the understanding of matter processes and energy formations can be activated in bounded and unbounded organisations. These studies prepared the basis for propositions 1 and 2, which in turn construct the argument for answering this question. In principle, by the organisation of matter processes, a relationship between architectural structure and an environment is increased and their differences are dissolved. In some cases, as argued above, it is difficult to speak meaningfully of two different aspects, rather than just understanding the structure and environment as one entity, which can be manifested from a minimum of four different approaches, as discussed in Environments (chapter 3). What the theoretical and experimental studies indicate are the potentials of activating these relations to increase constructions that are understood as extensions of the local environment, rather than as autonomous entities. This answer is also related to the arguments of maximum structures, proposition 4, and multiple authorships, proposition 6.

What is the basis for an architecturally elaborated construction model, and how can it be formulated and made instrumental for environmental architectures? (Q2)

The question points to the development of an architectural design methodology, which aims to allow tectonic constructions to be created based on environmental information. The basis for such a construction model was discussed and formulated in relation to the case studies on Tectonics (chapter 4) suggesting an underlying Element, System, Formation method of many constructions described as tectonic. Such a system is argued to be embedded into an additive approach. In extension, transformation processes were identified and proposed to extend the additive, responsive and adaptive properties. Both of these processes, additive and transformation, have been related to Semperian Stoffwechsel, proposition 5, and to the five causalities, proposition 6. This basis and its methodology has been applied as an instrumental approach in Probes (part 3), from the organisation of elements that are bound by a prescribed system such as Acoustic Tectonics I and II (chapter 7 and 8) to generative addition of elements by their matter properties such as Thermal Tectonics I (chapter 9) and to elements with inherent transformations by responsive behaviours such as Thermal Tectonics IV and V (chapter 12 and 13).

How can tectonics be oriented towards and become instrumental for an approach to environmentally sustainable architecture? (Q6)

The thesis Introduction (chapter 1) identified tectonics as an approach inclined towards structural articulations based on gravity. This observation and argument was later strengthened in Tectonics (chapter 4). However, by basing an environmental tectonic approach on the five causalities (proposition 3) enabled by the organisation of matter (proposition 1), it is possible for maximum structures (proposition 4) to become tangible. Tectonics then, becomes instrumental by its foundation on a broader set of causalities related to the environment and the human alike. This, in turn, allowed the discussion of joining in Environmental Tectonics (chapter 14). In this way, environmental aspects are oriented towards an instrumental approach for tectonic joinery. As mentioned in the Synthesis (chapter 14), this form of environmental tectonic articulation could be observed in the Thermal Tectonics II and V probes (chapters 10 and 13).

What modes of architectural instrumentation are applicable to the support of this orientation? (Q7)

What theoretical and instrumental assessment and environmental open-development models are needed to evaluate and evolve an environmental architecture? (Q3)

These questions are related to research question 5, as they ask what, rather than how, instrumental modalities support an Environmental Tectonics approach. While they were asked independently through the segregated introductory sections of Tectonics in Architecture and Computational Architecture, they can nevertheless be answered as a pair.

As argued through Semperian Stoffwechsel, the tracing of discernible steps increases the illegibility of a tectonic formation (proposition 5) and thus modes that exhibit gradual modifications can be stated as instrumental modalities. What was shown in Environments (chapter 3) and Tectonics (chapter 4) is that both additive and transformational processes are explicitly related to the active influence of environmental factors, from topography to humidity, acid and salt concentrations in the air. Hence, models that support the active revealing of discernible steps and the integration of environmental factors to inform these steps are applicable towards an Environmental Tectonics approach as formulated here. This in turn points to computational methods and models that enable such processes in architectural making. As initiating modes and models of such an approach to environmental architecture, atmospheric, thermal and acoustic aspects have been used as a basis for the formations within the specific models presented in Probes (part 2).

(Q8) *What computational methods allow the integration and active influence of environmental aspects on architectural making?*

(Q9) *What computational methods support the theoretical orientation of Environmental Tectonics as an agenda for a sustainable architecture?*

As with research questions 3 and 7, the two above questions can be answered in relation to each other, as the research indicates a joint answer.

In relation to computational methods and models, it was asked what processes could be embedded as an applied architecture. The theoretical and applied research pointed to two answers, both related to developmental processes. Based on natural computation methods, discussed in Computation (chapter 5), rewriting procedures and evolutionary algorithms exhibited gradual progressive behaviour through the interaction between multiple design agents. Both systems are also explicitly based on simple axioms – starting conditions – organised as singular elements, in a system, which through their interactions construct formations. These arguments form the basis for proposition 7. By extension, the described combination of these methods forms the foundation for epigenetic models (proposition 8), which in turn expands the integration of environmental influence and the gradual appearance (proposition 3). The experimental studies (chapters 7 to 13) indicate that these computational methods are adequate models for environmental integration that forms not only the architectural provisions, but also the computational model itself, as these are functioning by the continuous information of environmental factors to operate. While other computational methods than these may be applicable, they represent initiating and tentative computational approaches for an Environmental Tectonics approach to environmental sustainable architecture.

From these questions and the answers based on the theoretical and experimental studies, the overarching hypothesis and research question can be addressed. To reiterate, from the initial state of the art and the observation of indeterminate relationships between environmental construction methods in architecture and human-perceived sensations in architecture, the following hypothesis was formulated:

Environmentally sustainable architecture can be understood as matter that interacts, exchanges and forms into structure and space for the betterment of humans. Thus, a human-oriented environmentally sustainable architecture can be achieved by the organisation of matter.

This enabled the formulation of the overarching research question:

Can architecture be understood and instrumentalised as the organisation of matter towards a human-oriented environmentally sustainable architecture? (Qx)

When segregating the above question, it can be said that architecture can be *understood* as the organisation of matter towards a human-oriented environmentally sustainable architecture. This answer is based on the answer to research questions 1, 3 and 5. It can also be said that architecture can be *instrumentalised* as the organisation of matter towards a human-oriented environmentally sustainable architecture based on the answers to the other research questions.

In elaborating on this point,, it can be argued that the above question can be answered by stating the following:

Architecture is matter that forms sensations for humans. In a human-oriented environmental architecture, such as Environmental Tectonics, progressive matter organisations can be made instrumental in increasing the aesthetic dimensions in architecture.

This indicates that more profound models of human sensations and matter organisations can be studied to advance architecture's capacity in relation to the initiating problem statement. The thesis has identified and applied the evolutionary model as a method for human-environmental progressive design processes. Its extension into post-construction processes has been argued to be attainable by epigenetic architectural models, which have been discussed in Computation (chapter 5) and to some degree explored by the last design experiments in Thermal Tectonics IV and V (chapters 12 and 13). This in turn points to a potential research path by way of an advanced investigation of the progressive adaptive architectural model based on epigenetic processes. A reformulation of the research question, based on the theoretical discussions and design experiments, can then be offered by asking:

How are matter-based epigenetic models developed in a way that these evolve aesthetic architecture?

Inherent in this question is the acquired knowledge of progressive processes in architecture towards appearance, further fostered on the basis of the epigenetic model, including both Darwinian and Lamarckian evolutionary processes. Furthermore, the question applies the understanding that architectural aesthetics is based on the construction of environments for humans, effectively becoming environmental sustainable architectures. The consequence, potentially, is a decrease in the need to apply climate-damaging energy sources as the dynamic differences between a desired environment and a host environment are reduced.

15.4 Contributions

The thesis aimed to examine *why* it is important to integrate human sensations, *what* is needed for this integration and lastly *how* it can be done. From this, the twofold objective of identifying and elaborating a theoretical model and instrumental architectural design models, the core contributions to epistemological and architectural methodological models can be presented.

(1) The thesis is proposed to contribute to the epistemology of the ontology of architectural construction and specifically to the definition of tectonics in architecture by repositioning the theoretical grounding in the four causalities as derived from philosophy. While the knowledge of Heideggerian theory is not new, contemporary tectonic theories, in particular the branching of Digital Tectonics, are based on a more narrow definition of techné and construction, as discussed in Tectonics, Correlations and Synthesis (chapters 4, 6 and 14).

(2) The thesis contributes a theoretical architectural framework, entitled Environmental Tectonics, for an environmentally sustainable architecture based on human sensations and aesthetics in architecture. This differs from the associated and dissimilar approaches discussed in the Introduction, Environments and Synthesis (chapters 1, 3 and 14). The theoretical framework is based on the five causalities discussed and formulated in Synthesis (chapter 14), which are based on the arguments of the previous chapters. By this, it is argued to increase local specificity as a response to the first, second and third initial problems stated in the Introduction (chapter 1).

(3) The thesis contributes architectural design models created from a specific algorithmic method and model for generating solar exergy-based building forms in early design phases, as presented in Thermal Tectonics I (chapter 9). This is a response to the first initial problem stated in the Introduction.

(4) The thesis contributes prescriptive architectural design models through the formulation of the Element, System, Formation design system towards tectonic articulations. This method was identified, discussed and elaborated upon in Tectonics (chapter 4) and applied within the design experiments in Probes (part 2). This contribution attempts to address the fifth initial problem stated in the Introduction.

(5) The thesis contributes architectural design models that intend to facilitate the integration of thermal sensations simulations in early architectural design models driven by evolutionary processes, as discussed in Environments (chapter 3) and applied in Thermal Tectonics II to V (chapters 10 to 13). These studies are responses to the second initial problem stated in the Introduction.

(6) The thesis contributes architectural design models by forming and applying an epigenetic architectural model that integrates the dynamics of the five causalities defining Environmental Tectonics. This contribution addresses the fourth initial problem stated in the Introduction.

The significance and contributions of the thesis must be seen in the general and broad perspective of creating enriching environments for humans through increased aesthetic dimensions without damaging the natural environments in the process. This was and is the task at hand. Thus, the theoretical framework attempts to be broad in terms of possible general application while remaining distinct in terms of its human-oriented environmental approach to sustainable architecture. This is the case to the degree that specific design experiments have been conducted in full-scale architectural probes as concrete applied research demonstrators. The above contributions do not imply that end solutions have been found to the stated problems. Rather, they are tentative responses that require continuous advancements beyond this thesis.

15.5 Conclusions

The current framework rests on a broad theoretical base grounded in discussions from philosophy, neuroscience, biology, environmental engineering, computational science and architectural theory. From these perspectives, Environmental Tectonics is offered as an alternative to other approaches to environmentally sustainable architecture. Hence, the framework should be considered an addition to the existing orientations, and one candidate in the pool of architectural agendas, methods and models that support enriched environments for humans and sustainment of the natural environment through architecture. However, it nevertheless offers a critical positioning towards the current general approach in sustainable architecture of isolating humans in what are effectively becoming airtight buildings.

The proposed approach may face critique by neglecting the aspects of heat containment through lack of isolation between inner and outer temperature variations. However, as discussed in Environments (chapter 3), with reference to Moe (Moe 2013; Moe 2014) et al, energy as a quantitative measurement alone, with its focus on constructed closed-energy circles, is not solving the fundamental problems of environmental sustainability, nor does it fully recognise that any environment is in need of energy flux to sustain itself. In addition, other studies show that building envelopes can be developed to ‘breathe’ without losing significant amounts of energy through heat loss (Larsen et al. 2014; Craig 2014). Such studies are believed to support the arguments provided throughout the thesis towards greater articulated permeability in architecture.

In turn, it recognises that architecture is a shared authorship, influenced and organised as a non-discrete system, not confined to current architectural isolation principles of boundary making. In effect, the authorship is positioned dynamically between the acting parties, with the natural environment increasing its influence over time.

In relation to current prevailing theories of tectonics and strands of Digital Tectonics, the thesis presents a basis for Environmental Tectonics that is based on the five causalities, as adapted from Heidegger's four causalities, which in turn were derived from Aristotelian philosophy. In common with existing environmentally sustainable architectures, this thesis must be seen as an addition to the current tectonics in architecture approaches oriented primarily towards structural aspects and the expressive clarity of these.

While the theoretical propositions are grounded in early epistemology, pointing back to Greek philosophy, the applied experimental research rests on a much more recent knowledge base. This platform grew from the last century through the development of computational science and the relationship between evolutionary processes and matter-based computational processes. In this perspective, the epistemological grounding through design research and its direct applications is on much more uncertain ground. It is, however, argued that the theoretical and applied research is in alignment with a more robust thesis contribution by presenting propositions and arguments that are rooted in a comprehensive set of studies. As stated in Methodology (chapter 2), the circumstance of architecture as an applied science is to integrate aspects from philosophy to craftsmanship. Sekler's aforementioned phrase *'the construction of meaning and the meaning of construction'* (Sekler 1965) can thereby be understood in relation not only to his perspectives on tectonics in architecture, but also to architectural research.

15.6 Reflections on Methods and Results

The propositions and arguments presented here are believed to be based on results that are obtained through goal-oriented and systemic theoretical and experimental research. Nevertheless, the inquiry of the research has been conducted more as a web of investigations than as a strict linear procedure. Findings by both theoretical and experimental studies have produced paths for other studies that in turn have been pursued in divergent tracks for later correlation and convergence into new inquiries. The framework and conclusions are logically based on the conditions of these studies. As with any research, the study is as good as the research model, and the model, like the theory, is under constant development. Any research model making a representation of physical reality includes assumptions, as discussed above and in Methodology (chapter 2). It is commonly stated in the philosophy of science, and in particular in simulation models within the sciences, that a potential source of error within the inquiry is the assumptions that are making the model possible in the first place. Hence, searching for errors in the research results can often be approached by looking for errors in the line of assumptions that the inquiry is based on. Such research activities may be seen as parallel to the observations of phenomena that could be hidden along the potential errors of the study, as previously discussed.

The theoretical framework presented is a model that is based on a population of literary sources, discussed case studies and experimental studies based on empirically based simulations. While the literary studies and case studies bear the assumptions of being relevant to the inquiry, filtered by selection and positioning through a successive process, it is a different condition for the computational simulation models. While based on established mathematical models applied in keeping with international standards, they are rich in assumptions of matter processes and human physiological and behavioural processes. The latter assumptions, in particular, are currently under extended development, as mentioned in Environments (chapter 3), so as to include a more specified mathematical expression for human relationships to thermal sensations and humans' response patterns in relation to these sensations. The Adaptive Thermal model, applied in the assessment of Free-Running Buildings, is an example of such an approach. When new findings are done in these areas, they should be included anew in the studies here to examine the effect of the relationships between humans and the environment through architecture. Modifications to thermal and acoustic assessment are, nevertheless, not believed to change the fundamental conclusions of this thesis, as these are considered to modify the magnitude of affects and not the causalities of these in relation to constructing architectural environments.

Each successive inquiry and design research experiment of Probes (part 3) has been addressed through computational and physical prototypes. The empirical results as measured data, however, are primarily based on the digital simulation models. The reason for this is the near impossibility of constructing evolutionary processes, combined with acoustic and thermal sensations through physical constructions. By computation, the evolutionary processes search and illustrate the process of gradual appearance. In a way, it can be considered the equivalent to Marey's photographic technique revealing animal locomotion by observing multiple steps in succession. The idea of building hundreds of physical prototypes as a progressive process is considered unfeasible. This raises a potential critique of the models, as they are constructed on mathematical models derived from laboratory work removed from the contextual fieldwork of the applied research. However, in opposition to this argument on model validity is the added aspect of the ability to isolate factors in the simulation domain, enabling sensitivity analysis and application of delimited evolutionary processes that enhance the clarity of the process and the relationships between the variables examined. It was attempted in several of the physical probes to make on-site measurements, but the field data were affected by contextual noise, which obstructed successful measurements for later analysis. As an example, air velocities were measured in the study Thermal Tectonics II (chapter 9), but the size, location and context did not allow a sufficient filtering of disturbing elements to use the data as a basis for research conclusions. This learning of field analysis was, however, considered in the study Thermal Tectonics V (chapter 13), where a sensor network was installed in sealed containers behind the responsive envelope. The empirical data from the physical demonstrator is more legible, but it serves in this project as a singular positive integration of post-construction analysis from physical research demonstrators. These readings, however, also bear a set of assumptions, by the placement of the sensors, the logging time of the data and the possible aspects that may have influenced the data collection through the installed sensors, such as partial modification of the demonstrator while used for data logging. The latter argument might seem slightly unclear, but during data collection, thieves removed almost half of the responsive envelope, something less likely to happen in a laboratory setting.

If approaching the restated research question above, it is reasonable to follow the research design method of simulated environments and simulated evolutionary processes, as a physical experiment would potentially take hundreds of years to be conducted. The reason for this is that each evolutionary generation (iteration) would need to wait multiple ‘lifetimes’ of the Bernard Machine to adapt to local conditions and then use the adapted constructs as a basis for making the population in the Darwinian Machine. Such research is arguably most rigorously and systemically investigated in a digital computational domain.

With the mixed set of research methods applied within this thesis, it can be argued that possible errors inherent in assumptions of the inquiry stand a greater chance of being detected. In this way, the research project attempts to establish its findings and arguments on a broader base of research approaches to avoid flawed conclusions due to findings through singular methods. This approach is not always possible, but given the broad scope of the project, situated across humanistic and science domains, the applicability and possibility of a mixed-methods research design with the intent of more robust conclusions seems favourable. Furthermore, it may also allow conclusions on a broader set of aspects, rather than what can be deduced from the application of singular methods alone.

Accordingly, while the physical demonstrators have been used only to a limited degree for data collection, they have been applied as methods to test constructability, to detect potential unforeseen or re-definable variables not included within the computational models. Lastly, physical demonstrators are argued to be effective representations of the research inquiry and its immediate capacity for application in constructed architectures.

Finally, the thesis being based on the philosophy of science concept of progressive investigations for normative truths, the looping research design aligns with the basis for Environmental Tectonics by applying progressive processes towards an increased understanding and appearances of the specific inquiry.

15.7 Future studies

The restatement of the research question has already generated a possible future study based on this thesis. An examination, development and application of matter-based epigenetic models may be guided by an extended inclusion of information theory, as framed by behavioural cybernetic models. An extended understanding of environmental perception and the lasting effects on humans, as investigated in environmental psychology, could also be integrated. Studies of this kind would, however, require a deeper understanding and an extended operational description of the environmental impact on both psychological and physiological processes to be included in architectural models. Such studies are perhaps better conducted in fields that are adequate for assessing human behaviour, such as psychology, anthropology and sociology - leading to new interdisciplinary research constellations.

While the thesis has attempted to illustrate a theoretical and instrumental approach to environmentally sustainable architecture based on inert matter organisations, hints have been given about the integration of organic properties as a means of advancing the research. In addition, such processes could be informed by multi-matter organisations that, to a greater degree, exhibit and utilise the potentials of matter phase changes. Such changes may also strengthen the appearance of architecture by their continuous transformations.

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List of figures

Fig. 1.1 Anatomy of the dwelling by R. Banham. Drawing by Francois Dallegret (p.38)
Fig. 1.2 Centre Pompidou by R. Piano and R. Rogers. Photographer unknown (p.40)
Fig. 1.3 Velux Passiv Haus, Photographer unknown (p.42)
Fig. 1.4 Adaptive Model by Isak Worre Foged (IWF) et al, Photo by IWF (p.50)
Fig. 1.5 Greater London Assembly by Fosters and Partners. Photographer unknown (p.52)
Fig. 1.6 Catenary structure by StudioMap21. Photographer unknown (p.58)
Fig. 1.7 Mesonic Fabrics by Alisa Andrasek. Drawing by Alisa Andrasek (p.62)
Fig. 1.8 Serpentine Pavilion by T. Ito and C. Balmond. Photo by Jamen Brittain (p.64)

Fig. 2.1 Research position. Diagram by IWF (p.72)
Fig. 2.2 Research cyclic progression. Diagram by IWF (p.74)
Fig. 2.3 Theory path mapping. Diagram by IWF (p.76)
Fig. 2.4 Theory path map overview. Diagram by IWF (p.78)
Fig. 2.5 Summary of design research studies. Diagram by IWF (p.80)
Fig. 2.6 Research layers. Diagram by IWF (p.82)

Fig. 3.1 New York skyline. Photo by IWF (p.98)
Fig. 3.2 Nordic Pavilion by Sverre Fehn. Photo by Åke Eson Lindman (p.100)
Fig. 3.3 Roman Bath. Photo by Ben and Siv. (p.102)
Fig. 3.4 Blur Building by Diller Scofidio + Renfro. Photo by D.S. Architects (p.104)
Fig. 3.5 Thermal Bath in Vals by Peter Zumthor. Photo by Jennie West (p.108)
Fig. 3.6 Funktionskreis by Jacob von Uexküll. Drawing by Uexküll (p.110)
Fig. 3.7 Snail experiment by Jacob von Uexküll. Drawing by Uexküll (p.112)
Fig. 3.8 GC Prostho Museum by Kengo Kuma. Photographer unknown. (p.116)
Fig. 3.9 Media-TIC by Cloud9. Photo by IWF. (p.118)
Fig. 3.10 Royal Theater by Lundgaard&Tranberg. Photo by IWF (p.120)
Fig. 3.11 Vegetative membrane. Photo by IWF (p.122)
Fig. 3.12 Russians sunbathing. Photo by Elena Palm (p.128).

Fig. 4.1 Carribbian Hut. Drawing by Gottfried Semper (p.142)
Fig. 4.2 Tomba Brion Cemetery by Carlo Scarpa. Photo by James Butler (p.144)
Fig. 4.3 Locomotion. Photo by Etienne Jules Marey (p.148)
Fig. 4.4 Elements by Jørn Utzon. Photo by IWF (p.150)
Fig. 4.5 Kingo Houses. Siteplan drawing by Jørn Utzon (p.152)
Fig. 4.6 Kuwait National Assembly. Siteplan drawing by Jørn Utzon (p.154)
Fig. 4.7 First Traversina Bridge by Jürg Conzett. Photo by C.B.G. AG (p.158)
Fig. 4.8 Church of Christ the Worker by Eladio Dieste. Photo by Nicolas Barricola (p.160)
Fig. 4.9 Chidori assembly system. Drawing by Kengo Kuma Architects (p.162)
Fig. 4.10 Bending wood pavilion by AHO students. Photo by Lap Ming Wong. (p.164)
Fig. 4.11 Copper roof of Copenhagen Stock Exchange. Photo by IWF (p.166)
Fig. 4.12 Sandstone erosion Malta. Photo by IWF (p.168)
Fig. 4.13 Sandstone erosion Copenhagen. Photo by IWF (p.170)
Fig. 4.14 Brick wall deformation. Photo by IWF (p.172)
Fig. 4.15 Half-timbering deformation. Photo by IWF (p.174)
Fig. 4.16 Gantenbein Vineyard. Photo by Ralph Feiner (p.178)

Fig. 5.1 Elementary Cellular Automata. Drawing by Stephen Wolfram (p.190)
Fig. 5.2 Parallel computation scheme. Diagram by IWF (p.192)

Fig. 5.3 Growth of a plant geometry. Drawing by IWF (p.198)
Fig. 5.4 Silkeborg Museum by Jørn Utzon. Drawing by Jørn Utzon (p.200)
Fig. 5.5 Elementary Cellular automata ruleset. Diagram by IWF (p.202)
Fig. 5.6 Game of Life ruleset. Diagram by IWF (p.202)
Fig. 5.7 Game of Life system. Drawing by IWF (p.204)
Fig. 5.8 Genetic Algorthm procedure. Diagram by IWF (p.206)
Fig. 5.9 Roulette Wheel Selection. Diagram by IWF (p.208)
Fig. 5.10 Crossover procedure. Diagram by IWF (p.208)
Fig. 5.11 Strategies for response behavior. Diagram by IWF (p.214)
Fig. 5.12 Copper emissivity development. Diagram by IWF (p.218)
Fig. 5.13 Development with dynamic entities. Diagram by IWF (p.220)

Fig. 7.1 Evolutionary procedure. Diagram by IWF (p.240)
Fig. 7.2 Parametric model. Diagram by IWF (p.242)
Fig. 7.3 Evolutionary steps volume. Drawings by IWF (p.244)
Fig. 7.4 Evolutionary steps surface. Drawings by IWF (p.246)
Fig. 7.5 Musician playing in pavilion. Photo by IWF (p.248)
Fig. 7.6 Acoustic pavilion in context. Photo by IWF (p.249)
Fig. 7.7 Organisation of surface from sound sources. Drawing by IWF (p.250)
Fig. 7.8 Musician in pavilion. Photo by IWF. (p.252-253)

Fig. 8.1 Parametric model. Diagram by IWF (p.258)
Fig. 8.2 Milling pattern from computational process. Photo by IWF (p.260)
Fig. 8.3 Evolutionary model. Diagram by IWF (p.262)
Fig. 8.4 Acoustic design problem. Diagram by IWF (p.264)
Fig. 8.5 Computational raytracing model. Image by IWF (p.266)
Fig. 8.6 Acoustic pavilion. Photo by IWF (p.268-269)
Fig. 8.7 Reverberation time chart. Chart by IWF (p. 270)
Fig. 8.8 Acoustic pavilion in context. Photo by IWF (p.272-273)

Fig. 9.1 Green Lighthouse by Christensen&Co. Photo by IWF (p.278)
Fig. 9.2 Generative distribution algorithm 1. Drawing by IWF (p. 280)
Fig. 9.3 Generative distribution algorithm 2. Drawing by IWF (p.282)
Fig. 9.4 Relationship between energy and matter properties. Diagram by IWF (p.284)
Fig. 9.5 Solar energy forms. Drawings by IWF (p.286)
Fig. 9.6 Comparative analysis. Diagram by IWF (p.288)

Fig. 10.1 Aarhus University brickwork. Photographer unknown (p.294)
Fig. 10.2 Parametric model of brickwork. Drawing by IWF (p.296)
Fig. 10.3 Evolutionary model. Diagram by IWF (p.298)
Fig. 10.4 Airflow simulation through brickwork. Image by IWF (p.300)
Fig. 10.5 Interface of design space. Interface/diagram by IWF (p.302) [AR]
Fig. 10.6 Constructed brickwork probe. Photo by Henrik Christensen (p.304)
Fig. 10.7 Relationship between brickwork and airflow. Diagram by IWF (p.306)
Fig. 10.8 Front view of brickwork probe. Photo by Henrik Christensen (p.307)
Fig. 10.9 Detail of brickwork probe. Photo by Henrik Christensen (p.308)

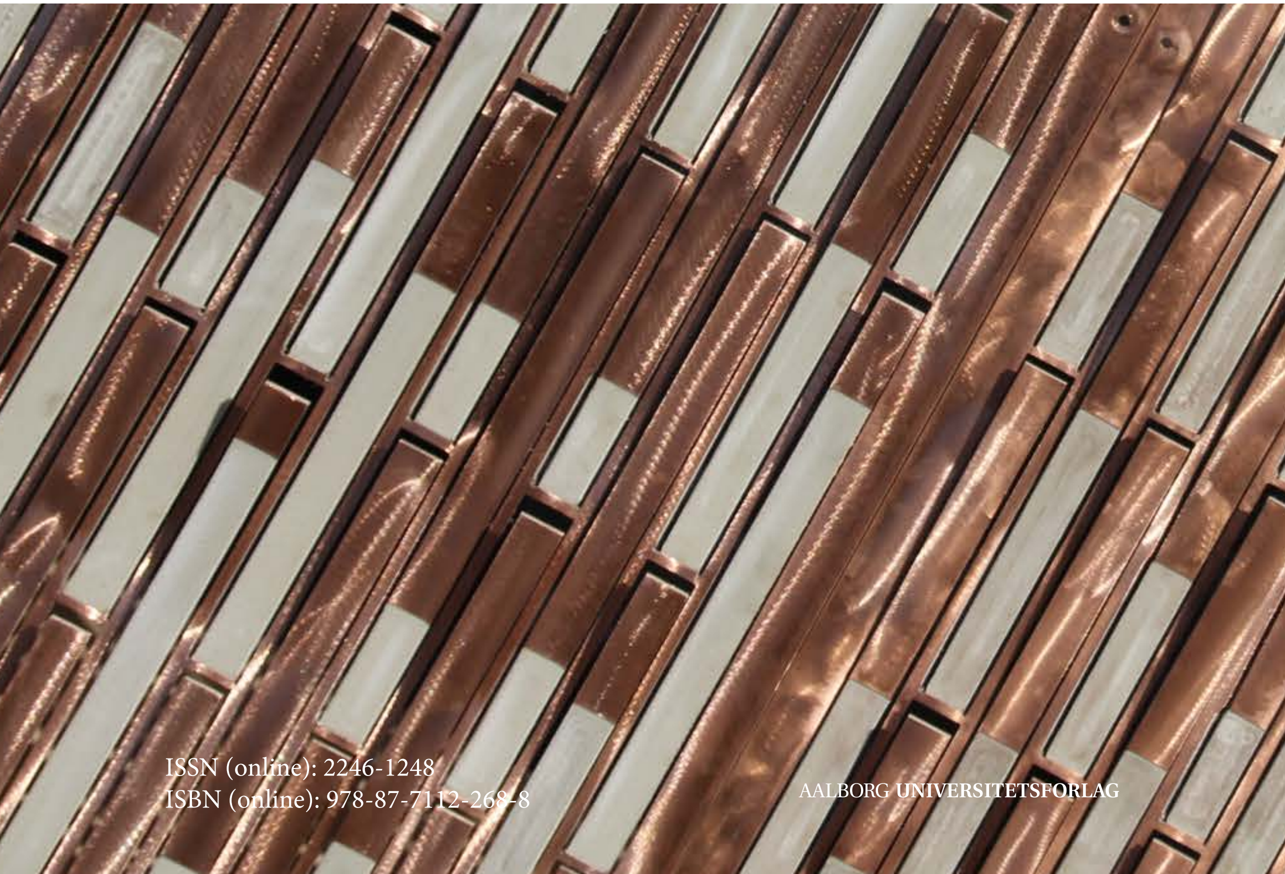
Fig. 11.1 Two colour brickwork. Photo by IWF (p.314)
Fig. 11.2 Temperature relations from emissivity. Diagram by IWF (p.316)
Fig. 11.3 Evolutionary model. Diagram by IWF (p.318)

Fig. 11.4 Simulation data feedback. Image by IWF (p.320)
Fig. 11.5 Elementary brickwork study. Image by IWF (p.322)
Fig. 11.6 Design model of brickwork. Image by IWF (p.324)
Fig. 11.7 Segment of brickwork bound. Image by IWF (p.326)
Fig. 11.8 Perspective view of evolved brick pavilion. Image by IWF (p.327)

Fig. 12.1 Responsive wood model. Photo by ICD Stuttgart (p.334)
Fig. 12.2 Bending behavior of composites. Image by IWF (p.336)
Fig. 12.3 Evolutionary model. Diagram by IWF (p.338)
Fig. 12.4 Sensitivity analysis. Diagram and drawing by IWF (p.340)
Fig. 12.5 Design experiment. Images by IWF (p.342)
Fig. 12.6 Thermal sensation simulation feedback. Diagram by IWF (p.344)
Fig. 12.7 Physical probe of composite structure. Photo by IWF (p.346)
Fig. 12.8 Physical probe of composite structure. Photo by IWF (p.348)

Fig. 13.1 Evolutionary model. Diagram by IWF (p. 354)
Fig. 13.2 Cross section of parametric model. Drawing by IWF (p.356)
Fig. 13.3 Light green copper patina. Photo by IWF (p.358)
Fig. 13.4 CNC milled copper composite. Photo by IWF (p.360)
Fig. 13.5 Acrylic plate and sensor in probe. Photo by IWF (p.362)
Fig. 13.6 Temperature variations inside probe. Graph by Kasper Worre Foged (p.363)
Fig. 13.7 Sensor network in probe. Photo by IWF (p.364)
Fig. 13.8 Sunlight and shadows inside probe. Photo by IWF (p.366)
Fig. 13.9 Full scale probe with milling pattern. Photo by IWF (p.367)

Fig. 14.1 Interior Gulf Stream by Rahm Architects. Drawing by Rahm Architects (p.372)
Fig. 14.2 SIM residence by Sean Lally. Photo by Sean Lally (p.374)
Fig. 14.3 Detail of behavioural composites. Photo by IWF (p.376)
Fig. 14.4 Detail of brickwork probe. Photo by Henrik Christensen (p.378)
Fig. 14.5 Five causalities. Diagram by IWF (p.380)



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