Generative Design Exploration: Computation and Material Practice

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Abstract

Today, computation serves as an important intermediary agent for the integration of analyses and the constraints of materialisation into design processes. Research efforts in the field have emphasised digital continuity and conformity between different aspects of a building project. Such an approach can limit the potential for significant discoveries, because the expression of architectural form is reduced to the varying tones of one fabrication technique and simulation at a time. This dissertation argues that disparate sets of digital and physical models are needed to incorporate multiple constraints into the exploration, and that the way the designer links them to one another significantly impacts the potential for arriving at significant discoveries. Discoveries are made in the moment of bridging between models, representational mediums, and affiliated processes.

This dissertation examines the capacity of algorithm—as a basis for computation—to diversify and expand the design exploration by enabling the designer to link disparate models and different representational mediums. It is developed around a series of design experiments that question how computation and digital fabrication can be used to diversify design idea- tion, foster significant discoveries, and at the same time increase flexibility for the designer’s operation in the design process. The experiments reveal the interdependence of the mediums of design—algorithm, geometry, and material—and the designer’s mode of operation. They show that each medium provides the designer with a particular way of incorporating constraints into the exploration. From the way the designer treats these mediums and the design process, two types of exploration are identified: goal oriented and open-ended. In the former, the exploration model is shaped by the designer’s objective to reach a specified goal through the selection of mediums, models, and tools. In the latter, the design process itself informs the designer's intention. From the kinds of interdependencies that are created between mediums in each experiment, three main exploration models emerge: circular and uniform, branched and incremental, and parallel and bidirectional.

Finally, this dissertation argues that the theoretical case for integral computational design and fabrication must be revised to go beyond merely applying established computational processes to encompass the designer and several design mediums. The new model of design exploration is a co-operation between algorithm, geometry, materials, tools, and the designer. For the exploration to be novel, the designer must play a significant role by choosing one medium over another when formulating the design problem and establishing design drivers from the set of constraints, by linking the design mediums, by translating between design representations, and by describing the key aspects of the exploration in terms of algorithms.
Acknowledgments

This doctoral thesis is the final outcome of a doctoral project that began on 20 December 2009 and also involved the completion of a licentiate thesis in September 2013. During this long journey, there have been many people to whom I am greatly indebted—a list that is perhaps too long to be fully included here. However, I would like to mention some of my colleagues and friends in particular.

I would first like to thank my main adviser for the thesis, my mentor and good friend Professor Oliver Tessmann, who taught me that what is not surrounded by questioning, deep thinking, and discussion cannot be genuine and true; who encouraged me to question new technology to its depths and to take risks in defining my research as I question the current discourse; and who supported me at every step towards finishing this thesis. Thank you, Oliver, for guiding me in a journey so stimulated by curiosity, and thank you for your consistently insightful input. I enjoyed our discussions of the work and receiving your frank opinions on it. You should know that I would not be satisfied with the end result today if not for the way you guided me to this end. I would also like to thank my second advisor, Jonas Runberger, who has been a mentor, colleague, and friend since my master's studies; Jonas, you have encouraged me to be original and think out of the box, to take credit for the work I have done, and to scrutinize it rather than merely following the main stream. Thank you for all the care and for sharing your knowledge.

I am very grateful to my final seminar opponent and reviewer Axel Kilian for insightful comments and discussion that have indeed had a significant impact on the work. I would like to thank Hélène Frichot for accepting the job of internal quality reviewer, as well as for her in depth review and encouragement in the review of the work. Hélène, your profound comments and in particular your positive attitude in conveying the result of the review gave me so much hope when I was about to fall apart due to the hardship of completing the work on time. I would also like to thank Craig Rodmore, who English proofed the work, for the incredible amount of time spent and the quality of the review. Craig, you have reviewed the work with passion, beyond merely English proofreading, and you gave me helpful comments on the content, which went far beyond your responsibilities.

The design and construction of the experimental prototypes presented in Chapter 6, Experiments, were carried out in design studios and advanced seminar courses that were founded and taught by Hamia Aghaiemeybodi and myself. I would like to thank Hamia for the great amount of time and effort. Hamia, the design studio and hence the prototypes would not have been successful without you. You have played a crucial role in my success; despite all the hard times, you have been always a brother, my best working partner, and my best friend. The realisation of these prototypes also involved many students without whom the projects would have not been possible. I am very thankful in particular for the amount of work and effort put into the experiments by the following students: Jonas Haraldisson, Lars Pettersson, Susanne Segerstein, Ante Lundgren, Karin Eknor, Emma

With regard to the experiments, I would also like to thank engineers Pooya Vahdati and Giuseppe Caprolu for the great amount of time they spent on computational fluid dynamic simulations and finite element simulations, respectively, for the projects presented in this research. Special thanks to Ulf Stenman and Lars Åström of the Complab at Luleå University of Technology in Sweden for assisting with construction issues, logistics, carpentry, and general knowledge, as well as for lending the workshop space.

Without the support of various companies and sponsors, none of the experimental projects would have been possible. Thank you to the following companies: Norrbottens, Byggmästareförening, XL Bygg Stenvalls, Jord Proffset AB, Samhällsbyggnadsinstitutionen vid Luleå tekniska universitet, Sundsvalls Profildekor AB, Biltema, and Laitis.

This doctoral thesis could have not been completed without the Lars Erik Lundberg Scholarship. Special thanks to the Lars Erik Lundberg Scholarship Foundation for funding this project; thanks in particular to Lottie Dyress Fred for her passion and support throughout the process.

In the course of this research I have been a guest faculty member and associate researcher at Carleton Immersive Media Studio (CIMS) at Carleton University in Ottawa and the John H. Daniels Faculty of Architecture, Landscape, and Design in Toronto, Canada. At CIMS I would like to thank Stephen Fai, Mario Santana-Quintero, and James Hayes for welcoming me and integrating me into the team. Stephen, you not only generously shared knowledge and office space with me but also included me in making many decisions, which made me feel like a part of the team. At the John H. Daniels Faculty of Architecture, Landscape, and Design, I would like firstly to thank Richard M. Sommer for giving me the opportunity to share knowledge with the faculty and generously providing me with resources and working space. Secondly, I would like to thank Brian Boigon, Robert Levit, Brady Peters, Benjamin Dillenburger, Terri Peters, and David Lieberman for integrating me into events, critiques, and fruitful discussions at the school. I would particularly like to thank Brian Boigon for helping me to conceptualise the chapters. At this school a number of people have always been there for me and have spent great deal of time and energy to ensure my comfort during the writing of this dissertation: Chuong Huy (Johnny) Bui, Thomas Abromaitis, Yuri Lomakin, and Vadim Aulov. I am grateful to you all.
At my home university, the KTH School of Architecture and Built Environment in Sweden, I would like to thank the following people for their support throughout this process: Helena Westerlind, Pablo Miranda Carranza, Daniel Koch, Martin Sjöstrand, Katharina Berndt, and Flora Bahram.

I would like to express warm gratitude to my dearest colleagues and friends Manuel Kretzer and Benjamin Dillenburger, who carefully studied this dissertation, and who offered insightful comments and moral support throughout the process.

I would also like to thank the examining committee and opponent for accepting the invitation to read and examine this dissertation. I am looking forward to hearing your points of view and recommendations about the direction that this research may suggest for the field and myself, as this end is just the beginning of my next journey.

And finally to my beloved family—my lovely brothers Farhad and Hamia, my parents Hassan and Forough, and my god parents Farhad and Kanjana. Thank you for your support and patience despite the hard times. I could not have pursued this research without your support and trust in me. You have made my life’s journey worthwhile. Thank you for letting me grow as an individual and for encouraging me to take the road less travelled.

In memory of my grandparents.
Clarification of Terms

The exploration model is composed of a series of models and is an assemblage of models in various media. The exploration model will be defined in Chapter 5.

The designer’s intention and design intent: design intent is used to emphasise the target form itself, whereas designer’s intention is used to emphasise the designer’s resolutions.

Manual physical model making and digitally controlled physical model making: In relation to the descriptions of the physical modelling processes throughout the thesis, the author makes a clear distinction between physical model making with the hand and with digitally controlled fabrication machines. As noted by Mark Burry, “the relatively slow process of handcrafting a model allows the designer to reflect as they are making their model”, whereas “rapid prototyping—a potentially highly iterative procedure—accelerates the process of putting ideas into action possibly at the expense of critical reflection” (Burry 2012). Like Burry, while making a distinction between the two processes of model making, the author’s aim is to reunite the two seemingly opposed approaches in the design exploration model. An Australian Research Council-funded project led by Burry, Homo Faber, is a valuable reference to this distinction and reconciliation. The project focused on digital model making and the role of models in the architectural design process. The academic team investigated ways that the new “technologically mediated model-making techniques” (Burry 2012) influence architectural design, and called for further exploration of the relationship between making through traditional craft and digitally based tools.
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Introduction
1.1. Generative design exploration

This thesis is situated in the context of the computer-aided design and computer-controlled fabrication of architecture. It is about generative design explorations that produce significant inventions and aid the designer in ideation. The thesis investigates a few fruitful generative exploration models for architects who use computation to design form and create buildings.

Design exploration is the act of searching for design possibilities and alternatives during the development of a design with respect to specific constraints and potentials in the context of future building—that is, architecture as material practice; the design exploration model is the domain where the constraints are established and their implications for possible design alternatives are explored. A generative approach to design involves applying a finite set of rules in order to produce all possible forms.

Generative design exploration involves a particular way of arriving at the design intent (geometric form). It involves formulating design-related issues, potentials, and constraints in the course of the design process and iteratively exploring consequent design alternatives using relevant and suitable computational tools and techniques. Computational tools and techniques enable the processing of information, and can be physical or digital. In contrast to conventional design, in which designers would directly draw the form of the building, design exploration by means of computational tools involves the designer developing a design model with the goal that the later interaction with this design model will allow for the discovery of possible design intents with respect to the formulated design issues. Today, digital tools are commonly used for computation and designing the exploration model, but architects such as Antoni Gaudí and Frei Otto also developed and designed the exploration model: famously, Gaudí’s hanging chain model and Otto’s soap bubble system allowed these designers to interact with a model and explore alternative forms that could not easily be designed and visualized with conventional projective tools (Figs 1.1, 1.2, 1.3 and 1.4).

Although an exploration model can be created using either physical or digital computational tools, advances in digital computational hardware, software, and algorithms have allowed for complex calculations and the processing of very large amounts of data. Using these advanced tools for design exploration, the action of searching for alternative design outcomes is a collaboration between human and machine (for computation). This collaboration has lead to design outcomes that were unthinkable a few years ago.

1.2. Design exploration through the model

The model is a tool for creating a design exploration domain. It bridges the gap between the design stage and the context of the future building by enabling the designer to incorporate constraints and potentials related to the realization of the design. Incorporating constraints and criteria by means of the model bounds and guides the exploration. In the “hanging chain” model briefly mentioned above, for instance, Gaudí used weighted
string to facilitate the exploration of possible forms of vaults with respect to gravitational forces. Since gravity was an actual constraint in the model, the curves were derived automatically as Gaudí modified the parameters of the model. Here it can be said that the implications of gravity as a constraint in the design exploration were introduced by means of a manual computational tool that enabled Gaudí to explore possible alternatives for structurally sound forms. The "hanging chain" model was a tool developed by the designer to aid him in exploring alternative design outcomes.

An architecture project is multi-constrained and therefore needs meaningful abstraction at different levels. Models of different types describe complex systems at multiple levels of abstraction. For example, the model that analyses the fluid dynamic situation of the building site, the model that analyses the economy of production of the building's parts, and the model that allows for the exploration of the geometric form of the future building are of essentially different kinds and levels of abstraction. On the other hand, no one model, however complex, will ever capture everything. Rather, by integrating several separate models and creating interdependencies between them, new insights can be gained and exercised in the design exploration. This dissertation aims to show that, indeed, the exploration model emerges from the integration of disparate models that are linked together by the designer, and that although multi-constrained it still has the potential for a multitude of outcomes. To combine the different models informatively and effectively in design exploration, the kinds of communication links created between them are important.

Today, computation in design utilises parametric-associative techniques and algorithm, through which multiple constraints can easily be made part of the exploration model. As a result of the capacity of computation, new interdependencies between models and the implications of multiple constraints can be explored simultaneously in different possible design outcomes. However, the question is how can designers use these computational tools to facilitate creative exploration, give rise to significant innovation and findings (which form new design outcomes or expressions), and aid the designer in ideation?

Moreover, in design in general and architecture in particular, the act of design exploration is not merely about arriving at an optimal design solution but is also about ways of modelling in which design innovation occurs and unknown solutions emerge out of modelling known constraints. Design exploration must not be confused with design optimisation, as their methods are developed based on essentially different approaches. While design exploration and design optimisation both require that the problem be formulated before the search and computation begin, in design exploration strategies are developed based on the further assumption that design conditions will be discovered little by little throughout the process. Thus while design optimisation moves towards convergence, the process of design exploration entails both convergence and divergence.

The use of algorithm and computational techniques in design has fundamentally affected the exploration model and the way designers can explore possible alternative outcomes and proceed in design process. Today, the object of design, the process of design, ways of conceptualizing architectural projects, and the role of the designer in the process have all changed. While no algorithm will ever replace the human designer, by using algorithms it is

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1. To the author, invention involves combining elements in new and unique ways that are relevant to architectural values and useful for people. Ingenious ways of employing digital computation and digital fabrication bring about novel discoveries in design.
possible to develop an exploration model that helps the designer to design beyond what is thinkable.

This research will explore the interdependent use of different digital and physical models within the extended design exploration model. Using algorithms, an intricate network of models can be created in which those models work together in a generative manner to enable significant innovation and findings. Algorithm and the parametric-associative technique play an important role in enabling this network and in computing the data, and the designer plays a significant role in creating and linking models in a way that increases the potential for significant invention and findings.

1.3. The exploration model in the context of architecture as material practice

This dissertation uses computer-aided design and computer-controlled fabrication tools to operate and develop a methodology for design exploration in the context of architecture as material practice. It is appropriate, then, to set out the detailed project framework and further contextualise the design exploration in the context of architecture as material practice.

1.3.1. Architecture as material practice

Architecture as material practice essentially revolves around (1) a way of working and thinking about design in which material and making are considered intrinsic to the design process and the realisation of the design idea itself (Thomas 2007) and (2) design approaches in which the materialization stage, traditionally the final part of the process, is one of the drivers in the articulation of form throughout the design process (Hensel, Sunguroglu, and Menges 2008, 35–36). Its ambition is to embrace design methods that break away from the hierarchical separation and dichotomy of the descriptive processes of form definition and the practical processes of materialization (Menges 2010)—a rift that has existed since the Renaissance as result of distinguishing architects, with their superior intellectual training, from master builders (Kolarevic 2008, 654; Menges 2015, 9).

This rift led to the development of representational tools for the architect: the mechanical tools of descriptive geometry that are used to create the formalised translation between a drawing and a building. Using these representational tools for ideation, for a long time designers and the process of design were detached from the actual act of building, and design methods were developed around form definition as something separate from the materialisation process. Traditional design tools supported a linear process. Design and its execution as building were two separate phases in a temporal sequence in which, although the designer’s awareness of manufacturing, construction, and assembly strategies may have influenced design decisions, the tools did not allow direct incorporation of such information into the conceptualization of the idea to make it an active agent in development of the design.

Contemporary computational tools available in CAD software enable architects not only to develop form with respect to the latter stages of design, but also to explore a broad spectrum of possible forms. Design exploration in the context of architecture as material practice as it is described in this thesis involves connecting the domain of exploration to the materialisation stages and using computational tools to explore design alternatives. This is usually done by making the constraints and potentials of the materialisation stage inherent to the design, then iteratively exploring consequent design alternatives and the implications of the constraints in those alternatives.
1.3.2. Constraints of materiality as design drivers

For design exploration in the context of architecture as material practice the specific context of the form is crucial, because that context is where most of the constraints are drawn from. As Christopher Alexander writes, “when we speak of design, the real object of discussion is not the form alone, but the ensemble comprising the form and its context” (Alexander 1964, 16). Alexander gives the example of designing a kettle: “An object like a kettle has to fit the context of its use, and the technical context of its production cycle” (Alexander 1964, 16).

When designing a building rather than a kettle, the context of use includes not only usability and production, but also site conditions that range from local cultural conditions to broader environmental factors such as gravity and climate. The framework of this research is set to discuss and examine the design exploration with respect to the following design contexts:

- the context of the production cycle: constraints of construction material, digital fabrication, and construction;
- the context of use: constraints of program framework and usability;
- the context of site: constraints of climate (such as wind and snow) and gravity.

These are the main contexts of the materialisation stage from which constraints are drawn in the experiments that form the practical component of this dissertation.

The constraints can also serve as design drivers in the exploration. As Axel Kilian points out in his practice-based dissertation, citing the work of both researchers and practitioners, constraints are usually seen as “limiting factors in design. But there is evidence in research... and architectural practice” that constraints can be design drivers and “can trigger the development of innovative design solutions and are a powerful way to drive the design exploration” (Kilian 2006, 16).

2. The rift between the design process and the materialisation stage began in the Renaissance and was increased by the empirical rationalism of the seventeenth century, which led to the separation of geometric and mathematical knowledge from architecture. The Cartesian-Newtonian emphasis on empirical rationalism led engineering towards a more theoretical approach and caused it to be considered a field distinct from architecture. In this separation, geometric and mathematical research followed engineering and not architecture (Rubin 1979, 20–21).

3. As mentioned previously, the current digital tools and their affiliated computational technologies enable the integration of constraints from later stages of the design process into earlier ones.

4. Constraints such as geometric ones related to the representation and tools for representation do not necessarily come from context; rather, they are constraints imposed by the tools used for design.

5. “From a purely descriptive standpoint we have no way of knowing which of the infinitely many relations between form and context to include, and which ones to leave out. But if we think of the requirements from a negative point of view, as potential misfits, there is a simple way of picking a finite set. This is because it is through misfit that the problem originally brings itself to our attention. We take just those relations between form and context, which obtrude most strongly, which demand attention most clearly, which seem most likely to go wrong. We cannot do better than this” (Alexander 1964, 26).

1.3.3. Bounding the exploration by modelling constraints

By making the constraints of the materialisation stage inherent in the exploration model, it is possible to embed the designer’s intentions and bound the exploration. As discussed above, a significant predigital precedent is Gaudí’s “hanging chain” model, in which the implications of gravity as a constraint in the design exploration are exercised through a manual computation tool in a physical environment. This model limits the exploration to structurally sound forms (Fig. 1.1). A precedent from earlier in the digital age is Frank Gehry’s paper strip model, in which, by choosing a paper strip as a medium for physical modelling, the exploration was limited to forms that were buildable from sheet material. This was a manual computational tool in a physical environment, and the forms assumed by paper in small-scale physical models were scalable to counterparts in the full-scale construction (Fig. 1.5).

In both of these cases, the exploration model is neither neutral nor open-ended: it already contains the designers’ intention—in the case of Gaudí through the way of modelling (procedural mode of physical computing), and in the case of Gehry through the selection of a modelling medium which is capable of computing the form (paper strip as a manual computational tool). Through the designer’s interaction with the model, alternative outputs are generated; by virtue of the way of modelling, the implications of the constraints are explored in the alternative outputs. However, in both cases—with Gaudí as a result of unsophisticated design tools, and with Gehry as a result of lack of expertise and limited software capabilities—the early exploration was disconnected from the rest of the design process (Fig. 1.6). In other words, the development of the exploration model was disconnected from the development of form description and form realisation. The designer’s intention and the expertise for actual building were separated, and the translation of form into buildable components was developed after establishing the form itself. To proceed to the realization stage, Gaudí used mechanical representational tools and descriptive geometry to create two-dimensional representations in the form of drawings; in Gehry’s work, the design exploration model (paper model) remained separate from the digital description that enabled the realisation of the design: a digitizing arm was used to digitize and scan the form assumed by the paper, and that form was then digitally represented in the form of a developable surface in CATIA software, then post-rationalised into parts to be realised from construction material.

Moreover, in both of these cases the exploration model was developed around only one constraint and was very limited: it was not expanded to integrate more constraints, and did not develop or continue into all stages of the design-to-production process.
Whether or not Gaudí knew of the earlier work defining geometry with parametric equations, Gaudí certainly employed models underpinned by parametric equations when designing architecture. Gaudí’s hanging chain model automatically computes the parametric outcomes. Rather than manually calculating the outputs from the catenary curve’s parametric formula, Gaudí could automatically derive the shape of catenary curves through the force of gravity acting on strings. This method of computing was enlarged by Frei Otto to include, amongst other things, minimal surfaces derived from soap films and minimal paths found through wool dipped in liquid (Davis 2013, 205).

Examples of employing structural analysis models for generating the design geometry and topology can be seen in Sigrid Adriaenssens, Philippe Block, Diederik Veenendaal, and Chris Williams, eds., Shell Structures for Architecture: Form Finding and Optimization (London: Routledge, 2014).

1.3.4. Algorithm for multi-constrained digital exploration

An architecture project is multi-constrained, and within multi-constrained design processes there are various sets of design intentions that have to be modelled. With the introduction of the computer and progress in computational techniques for architects and building experts (engineers, fabricators, etc.), multiple constraints can be modelled and captured to drive the early design exploration. Moreover, it is possible to develop computational geometric and analytical models that work together in such a way that the designer can interact with the model to virtually explore design alternatives with respect to the constraints of real-world contexts. For instance, certain geometric requirements needed for fabrication can be modelled in the geometric model, and the results of the structural analysis can be linked to the geometric model in a generative manner to generate the design geometry and topology. An example is the British Museum Great Court Roof designed by Foster and Partners together with Buro Happold, Engineers (Fig. 1.7). Using computational techniques—specifically, the dynamic relaxation method combined with parametric-associative geometric modelling of the roof—multiple constraints related to aesthetic, structural, economic, fabrication, and assembly aspects of the roof become part of a single exploration model. As noted by Chris Williams, “a combination of analytical and numerical methods was developed to satisfy architectural, structural and glazing constraints. Over 3000 lines of computer code were specially written for the project, mainly for the geometry definition, but also for structural analysis” (Williams 2001, 434).

By integrating various geometric and analytical computational models, the exploration model of the roof allowed the design team to explore an overall form that was structurally sound with respect to the size of the triangular glass components, which themselves were constrained in size. According to Williams, “the limitation on glass size was the controlling factor in choosing the structural grid” (Williams 2001, 439; Fig. 1.8). In the scripted description of the roof’s form, a mathematical function was used to control “the maximum size of the glass triangles which occur near the centre of the southern

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7. “Whether or not Gaudi knew of the earlier work defining geometry with parametric equations, Gaudi certainly employed models underpinned by parametric equations when designing architecture [...] Gaudi’s hanging chain model [...] automatically computes the parametric outcomes. Rather than manually calculating the outputs from the catenary curve’s parametric formula, Gaudi could automatically derive the shape of catenary curves through the force of gravity acting on strings. This method of computing was enlarged by Frei Otto to include, amongst other things, minimal surfaces derived from soap films and minimal paths found through wool dipped in liquid” (Davis 2013, 205).

8. Examples of employing structural analysis models for generating the design geometry and topology can be seen in Sigrid Adriaenssens, Philippe Block, Diederik Veenendaal, and Chris Williams, eds., Shell Structures for Architecture: Form Finding and Optimization (London: Routledge, 2014).
boundary” (Williams 2001, 439). Though in his dissertation Kilian speaks of a “design explorer” rather than an exploration model, this example can be seen as an exploration model that, as Kilian writes, utilises “both optimization and geometric principles to simultaneously enforce constraints” (Kilian 2006, 40). In this case, “the structural constraints are enforced through a design surface principle. The aesthetic appearance emerges from the dynamic relaxation distribution” (Kilian 2006, 40).

Using the computer and computational techniques has enabled integral computational design processes. Through scripting and coding, the geometric definition of form is developed and the geometric model is created. By linking the computational geometric and computational analytical models, the domain of design is informed by the real-world context of building. Algorithmic and parametric-associative techniques in the form of descriptive procedures and rules are used to digitally model various design intentions, and then to explore their implications in design alternatives—generating changes to geometric properties and other attributes as parameters are changed.

By virtue of an integral computational design process, a digital exploration model can be created that enables the designer to virtually explore design alternatives constrained by the conditions of real-world contexts. Like the exploration model described above, the digital domain of exploration is neither neutral nor open-ended: it already contains the designer’s intention in form of descriptive parameters, procedures, and rules. These descriptive parameters, procedures, and rules are the algorithm, which will be studied in depth in Chapter 4. When using the algorithm for exploration, the exploration model is no longer disconnected from the rest of the design process as it once was. The new digital exploration model is created from the integration of experts and geometric models, and it can expand throughout the design process, all the way to producing the instructions for machining and fabrication of parts (Fig. 1.9). Nevertheless, while CAD design tools allowed the designers of the Great Court Roof to consider fabrication constraints as an intrinsic part of form definition and design, material practice—making itself—was not an integral part of the design process, and the realisation of the design idea did not involve material practice and making as a way of working and thinking about design.
1.3.5. Algorithm for integral digital and physical exploration

Today, extensive access to digital fabrication machinery and generic robotic arms in architecture schools and some architecture offices has enabled integral digital and physical exploration. In this approach, material thinking and making are once again integral to the design process, and the realisation of the design idea involves making and crafting as a way of working and thinking about design. Exploring the description of form together with empirical materialisation of it involves, on the one hand, embodying the constraints in the exploration model when making the design definition, and, on the other hand, persistent materialisation using digital fabrication tools and feeding back the designer’s evaluation of the result to the form definition to refine the design iteratively.¹¹

“Today . . . it appears that a large part of contemporary architecture is determined by algorithmically established design procedures” (Willmann et al. 2012, 13). Using the algorithmic, programming, and scripting environments available in CAD software it is possible to encode the constraints of materialisation early on and make them inherent in the design (Gramazio and Kohler 2008; Kolarevic and Klinger 2008; Gramazio, Kohler, and Oesterle 2010). Using algorithm, the assembly logic of a material system and the logic of computer-numerical-control (CNC) fabrication machinery are encoded in the logic of form and become part of a generative design process at an early stage (Menges 2008; Gramazio and Kohler 2008; Gramazio, Kohler, and Oesterle 2010; Gramazio, Kohler, and Langenberg 2014; Kolarevic and Klinger 2008; Willmann et al. 2012). Here, “the central issue is not the design of a form; rather it is the design of a production process. . . . Thereby conceptual commonalities between the construction of a building component and the programming of a computer become apparent” (Willmann et al. 2012, 13). Gramazio and Kohler refer to this as “Digital Materiality,” in which the design concept “evolves through the interplay between digital and material processes in design and construction” (Gramazio and Kohler 2008, 7). “Digital Materiality is characterized by material precision and clarity. . . . It is a design and construction process controlled in all its details by the architect, a fundamental balancing or weighing of real possibilities, so to speak, during the process of making” (Willmann et al. 2012, 14). “In addition to the intricate relations between material, form and performance, computation offers the possibility of integrating processes of manufacturing and fabrication in the design exploration” (Menges 2012, 20). This is also known as an integral computation and materialisation process. As noted by Branko Kolarevic, “the new techniques and methods of digitally-enabled making are reaffirming the long forgotten notions of craft, resulting from a desire to extract intrinsic qualities of material and deploy them for particular effect. As such, interrogating materiality is fundamental to new attitudes towards achieving design intent. (After all, architecture is fundamentally a material practice)” (Kolarevic and Klinger 2008, 7). Such links “to the tradition of construction” allow “changes [in] the culture of architecture, both in its expression and in its productive capacity” (Gramazio and Kohler 2008, 9).

Today, modelling various design intentions in a design exploration model is a relatively easy task. In recent years, much has been achieved in enabling integral computation and materialisation by linking computational geometric and computational analytical models and

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10. “Algorithmic is a term that refers to the use of procedural techniques in solving design problems.” (Leach 2010, 9)

11. The new exploration space itself contains design-to-production processes.
digital fabrication machinery. There is a common "desire to celebrate the accomplishments of a geometry based computational design approach excelling at producing images and instructions for machining and fabrication" (Kilian 2012, 45). The celebration of this achievement is usually manifested in design works that exploit the potential of digital fabrication tools for the production of complex geometries. However, as Kilian notes, “design should not be solely about the execution of established processes” but it is a more “complex task” that relies on the designer’s mind (Kilian 2012, 44) and expertise in formulating the factors involved in the project framework using design tools and mediums. Moreover, the initial creation of the idea and the realization of the design cannot be reduced to the implementation of the material construct (the building part): as is commonly discussed in the field of computational design, fabrication influences design and vice versa.

In the current discourse there is a lack of discussion about creative design exploration, early design conception (ideation), the role of the designer, and design. There remains an open question as to how to use computation in the design exploration and how to incorporate multiple constraints. The exploration must be specific and at the same time sufficiently flexible to allow creativity, increasing the potential for arriving at significant invention and aiding the designer in ideation. What are the roles of the designer and the design itself in a project, beyond enabling the building of complex geometry?

1.4. Research objectives and questions

An important design medium that enables integral digital and physical exploration is the algorithm, which is accessible to designers via programming and scripting environments and algorithmic graphic interfaces in CAD software. This research shows how the use of algorithm in CAD enables the creation of a new, expanded, generative exploration model in which new insight is gained by creating multiple interconnections and interdependencies between disparate models. Algorithm and parametric-associative techniques enable the computation of the intricate network of data; the designer, who is rarely discussed in the current computational discourses and practices, plays a significant role in increasing the potential for significant inventions and creative exploration. The research question is:

How can computation and digital fabrication be used to diversify design ideation, foster significant discoveries, and encourage aesthetic expressions of the product, and at the same time increase the flexibility of the designer’s operation in the design process?

This thesis seeks new exploration models that use computation and digital fabrication to enable creative exploration and aid the designer in ideation. To answer the research question, the thesis investigates the benefits of algorithm and parametric-associative technology for creative design exploration and their relation to the designer’s intention and the process of ideation. It examines their capacity to enable the designer to expand the exploration model to integrate several separate ones and create new interdependencies between these models. It also investigates their shortcomings and the resistance they put up for creative design exploration. To explore and understand the benefits and shortcomings of computation by means of algorithm and parametric-associative techniques as a method for design exploration in the context of architecture as material practice in detail, the research sets out to:

- understand the concept of algorithm and present the way in which algorithm is currently made available to the designer in CAD software;
• understand the concept of algorithm with respect to the act of design, the designer’s intention, and the project framework—the ways the designer can conceptualise constraints and define design intention using algorithms, and algorithm’s impact on the realisation of design itself and the reformation of the designer’s initial intention;

• present a number of ways in which algorithm is currently employed in architecture as material practice;

• identify and critically analyse the impact of algorithmic tools on creative design exploration and the exploration model.

The thesis speculates that formalising designs and establishing constraints in an exploration completely by means of algorithm (that is, formal logic) would limit the creative exploration and reduce the potential for significant invention. Thus another objective of the research is to find out if diversifying the mediums that incorporate the constraints in an exploration improves the creative exploration, pushing it to further embrace the designer and leading to significant invention. To investigate this, the thesis examines the incorporation of constraints by means of geometry and material in addition to the algorithm. Geometry and material are other mediums that can be used to formulate constraints, and involve the designer’s visual imagination and hand, respectively, in the process of exploration.

Considering the roles of designers and design, Kilian points out that design is a complex task that “goes far beyond the geometric and numerical representation of current computational practices” and “happens in designers’ minds regardless of the involvement of computation” (Kilian 2012, 44). However, the author believes that the designer’s mind does not work in isolation from design mediums, but rather together with them: design definition relies on the designer’s expertise in formulating a design by means of a particular design medium. The design mediums themselves are prescriptive and guide the way the designer operates. Therefore it is important to know the potentials and limitations that the mediums of algorithm, geometry, and material have for the designer’s mode of operation and the exploration.

The question this research examines is not only how each of these mediums enables the designer to establish constraints in an exploration, but, beyond that, how algorithm and the current digital tools enable the designer to use these mediums interdependently in a creative and generative way. And what role does the designer play in this set-up? In response to this question, four experiments were conducted that incorporate constraints into the exploration by means of geometry, material, and algorithm and exercise their synergy in practical ways.
1.5. Approach and modes of research: practice-based research

This dissertation was developed around a set of experiments that examined the employment of digital design and fabrication tools and algorithmic and parametric-associative techniques for design exploration. The experiments worked within specific project frameworks with the ambition of producing large-scale prototype structures. The purpose of producing large-scale prototypes was to reflect actual building projects, in which the scale has an impact on the exploration. What was attempted and achieved in earlier experiments informed the design of the framework for subsequent ones. From the series of experiments, a schematic theoretical model of exploration was worked out.

The written component of the dissertation is a retrospective account of the experiments. The role of the experimental projects and the present text is to focus on the interdependencies between the designer, the design mediums (geometry, algorithm, and material), and the digital design and fabrication tools that enable the new exploration model. By externalizing and reflecting on the design-to-production processes of the experiments through a combination of diagrams, images, and textual descriptions, more can be learned and a new understanding of the role of computation in design exploration can be achieved. As such, this dissertation does not present a sanitized version of the use of integral computation and materialisation methods for design, but rather exposes the discrepancies in the transitions, in the translations, and in the feedback within the processes, so that both the author and the reader can learn from them.

The research conducted can be categorised as practice based. Linda Candy describes practice-based research as “an original investigation undertaken in order to gain new knowledge partly by means of practice and the outcomes of that practice” (Candy 2006, 3). In practice-based research, the “claims of originality and contribution to knowledge may be demonstrated through creative outcomes which may include artefacts such as images, music, designs, models, digital media or other outcomes such as performances and exhibitions” (Candy 2006, 3). In this dissertation, originality and contribution to knowledge are demonstrated through the creative design-to-production of large-scale physical prototypes in the form of pavilions that can accommodate humans, their installation in physical sites, and the integral retrospective revisiting of the experiments in the form of academic publications. While the significance and context of these experiments are described in words in this dissertation, a full understanding can only be obtained with direct reference to the processes of design and the outcomes of the experiments.

Practice-based research is more widely established in Europe, Australia and UK than elsewhere, and is a term that has provoked a series of misunderstandings and disagreements in the research community. For instance, considering the term problematic, Daniela Buchler notes that “it is not clear, for example, what proportion or contribution from practice to academic research would characterize this research sub-group. The converse concept, that academic research would not have a practice aspect, is also not persuasive. . . . Even academic research that is developed within the traditional scientific disciplines contains practical elements such as experimentation, data collection, observation and interviewing, for example” (Buchler et al. 2009, 7; Biggs and Buchler 2008, 27). The term “practice-based research” as it is used in this dissertation refers to research in which practice is the driver of the research and the production of new knowledge—not research that merely contains practical elements or activity. Practice-based research may not necessarily have a pre-Formulated hypothesis which the researcher conducts experiments for and tests against by practice; rather, the practice conducted may generate questions, hypotheses, and knowl-
edge. Professor Mark West of the Centre for Architectural Structures and Technology (CAST) developed knowledge in his research by working with tangible material and the full-scale production of cast concrete prototypes. He describes the fundamental research and work at CAST in this way: “it’s not like having a bullseye that you try to shoot the centre of with a rifle; it’s more like shooting a shotgun against the wall and drawing bullseyes around those holes. You never miss. Always find something. And the intellectual problem is to identify what it is you found and to see its use-value in some way or not. So by playing, we can find” (West 2011).

In this mode of research, the researcher’s experience—practical and theoretical knowledge—of the research context and expertise in practice is critical. In English, the word “experience” is used to cover a meaning for which German has two words: Erfahrung, which refers to practical knowledge and is used for when someone learns, goes through, gains, or has an experience of something, and Erleben, which on the contrary refers to affect and is used to express something out of our system of understanding that we have to deal with. For example, in the case of a carpenter, who has experience in carpentry—that is, a certain system of understanding and a way of dealing with something (a field)—one would speak of Erfahrung, whereas one would speak of Erleben in reference to someone who had experienced a war zone (Hart 1992, 50; Kant and Guyer 1998). An understanding of this difference is crucial in this thesis, in which the role of author is that of someone who goes through the processes of designing and producing the prototypes. The author is also a designer, who both has experience and gains new experience—Erfahrung—through designing and building processes. ¹³ She informs the design process with her previously gained experience and knowledge of how to form and how to build. ¹⁴ Similarly, she sets the framework of each experiment upon the learning of the previous one.

Practice-based research positions the processes of the practice, the outcomes of the practice, and the practitioner at the centre of the research. Knowledge production relies on processes, outcomes, and debates about the role of the author herself as the design practitioner and her work in the research context (Candy 2006, 3). At the same time, the writing should not be overlooked, as the process of writing also involves design—the emergence and reformation of ideas. This research is developed in a cycle of practical experimentation and theoretical writing. The theoretical hypothesis is formed and reformed in the feedback loop between the cycle of practical experimentation and writing, just as the framework of each experiment was formulated based on earlier ones. By playing and practicing, pushing the borders and exploring potential, new things were found and new questions emerged—and in fact sometimes this did not occur, but the exploration went on.

The interest in building physical prototypes to explore a research agenda is not without precedent. An example is the Digital Crafting research network, which was organized in the period of 2009 to 2011 and structured around hands-on workshops and seminars in which physical prototypes were built to explore “how traditional material techniques are challenged through digital fabrication,” the associated parametric-associative techniques, and generative design processes (Thomsen et al. 2013, 12). Other examples are the Institute for Computational Design (ICD) and the Institute of Building Structures and Structural Design (ITKE), where research is conducted around designing and constructing temporary, large-

¹³ This is done together with the students. It is teamwork, but the author guides both the project teams and the overall practice.

¹⁴ This dissertation is a reflection of my experience throughout the last fifteen years, especially the last five years of practicing in the field.
scale prototypical structures in the form of pavilions. Other relevant examples are the large-scale prototypes designed and produced as the core of research in the Architecture and Digital Fabrication Group at ETH Zurich, chaired by Professors Fabio Gramazio and Matthias Kohler, with the aim of exploring architectural operability of the new computational design and digital fabrication tools.

1.6. Structure of the dissertation and introduction to the chapters

This dissertation is composed of six chapters that focus on technological tools (Chapter 2), the mediums through which one designs (Chapters 3 and 4), the generative exploration model (Chapter 5), the experiments conducted (Chapter 6), and the Conclusion and Reflections (Chapter 7). The investigations of the mediums of design—algorithm, geometry, and material—are broken into two chapters, based on their relation to the designer’s mode of operation: logic versus intuition.

1.6.1. Chapter 2—Design exploration using digital tools

This chapter focuses on the development of the tools and the research context. In it the author presents a brief historical overview of the progress in computer-aided design tools and their coupling with digital fabrication machinery for exploring architectural form and expression. She situates the research in the context of integral computation and materialisation. The importance of algorithm and the parametric system for enabling the designer to employ integral computation and materialisation as a design method is highlighted. The chapter looks at the tendency that exists in the current discourse to achieve integration, with an emphasis on digital continuity and conformity between different aspects of a building project. It ends with a discussion of the gap the author sees in the current practice and discourse of computational design and materialisation, which is where this research makes a contribution.

1.6.2. Chapter 3—Algorithm: Logical design medium

This chapter investigates the algorithm as a logical medium of design. It investigates the use of algorithms as a basis for practicing computation in architectural design with regard to material practice, and develops an understanding of the benefits and shortcomings of algorithmic approach for creative design exploration. The concept of algorithm and the particular way that it is available to designers through CAD software is presented, and its relation to creative design is critically analysed. In this chapter, the author identifies a number of ways in which algorithms have been employed in architectural design with respect to material practice. It presents the ways that algorithms allow designers to incorporate multiple constraints, explore design alternatives, expand the exploration model, and test new interdependencies between disparate models and mediums, with respect to the experiments. Finally, it is shown that using algorithm as the only design medium limits the exploration to logical and numerical operations. As such it must be used in synergy with other mediums of design.

1.6.3. Chapter 4—Material and geometry: Spatial design mediums

This chapter focuses on material and geometry. These mediums’ spatial and topological properties allow the designer to operate with them tactilely, in the case of material, and visually, in the case of geometry, rather than only through reason and logic. The possibilities
of employing these mediums to establish constraints in the exploration are explained with regard to the experiments.

1.6.4. Chapter 5—The generative design exploration model

In this chapter the author develops a description of the new exploration model. Mediating between the previous chapters and the following one, this chapter presents the interdependencies that exist between tools, models, and mediums—algorithm, geometry, and material. It presents the new exploration model as a model that encompasses many types of models, their mediums, their linkages, and even the designer. The new exploration model is enabled by the use of algorithm and the application of computation in design. Whereas the description of the exploration model was developed in the course of and after concluding the experiments, in this dissertation book it is presented prior to the Experiments chapter. This is so that it can function as a prologue to the experiments.

1.6.5. Chapter 6—Experiments

This chapter is a retrospective look at the experiments that were conducted to investigate the research question “how can computation and digital fabrication be used to diversify design ideation, foster significant discoveries, and encourage aesthetic expressions of the product, and at the same time increase the flexibility of the designer’s operation in the design process?”

The four experiments are presented in chronological order and were originally named Honeycomb, Strip, Hypar, and Hyperbolic Paraboloid. From the way the design mediums were linked to one another in these experiments, three main exploration models are identified (Fig. 1.10). These exploration models are:

- **Circular and uniform**, for a goal-oriented exploration that already contains an assumption about what is to be designed. Links begin and end at the same model, connecting a few subsequent models to earlier ones informatively in a circular fashion. This model is illustrated in Experiment 1, Honeycomb, and Experiment 2, Strip.

- **Branched, incremental, and diversified**, for an exploration that does not contain an assumption of what is to be designed, but rather grows and is open ended. The exploration is treated as a drifting design problem, and new influences are incrementally introduced at every step of the exploration. New features can emerge from hybrids of diverse models. This model is illustrated in Experiment 3, Hypar.

- **Parallel and bidirectional**, for when more than one influence is explored at a time. This is contrasted with the circular and incremental exploration, in which only one event occurs at a time and there is a hierarchy of searches in reference to influences. This exploration model involves the simultaneous linking of multiple mediums and models of different characters to a node model bidirectionally and exploring design alternatives at the same time. The bidirectional links between two models or mediums allow the designer to explore the design solution in two directions. A design solution is found
when the two frontiers of exploration meet. This exploration model is illustrated in Experiment 4, *Hyperbolic Paraboloid*.

The four experiments show the actual interdependency that exists between the tools, the mediums of design, and the designer. Moving from the first experiment to the last, a more differentiated discussion around the role of algorithm, geometry, material, and design itself can be made. As the author transitioned from one experiment to the next, the way of treating the algorithm, geometry, and material for design exploration changed. The language the author uses to describe the experiments changes from one experiment to another, in order to emphasise the shift in her own understanding of the interdependencies that can be created between algorithm, geometry, and material. The four experiments are as follows:

**Experiment 1 (Honeycomb):**  
Circular and uniform exploration model

In this experiment a uniform cycle of digital design to production is developed. This involves circularly linking the geometric model and its subsequent models in the digital cycle of design to production (Fig. 1.11). The emphasis is on digital continuity and conformity between different aspects of a building project. This means that analytical simulation models are developed in a way that can be linked to the geometric model in a circular and generative manner in order to generate the design geometry and topology. Computation is used for the integration of digital geometric, simulation, and fabrication models with intention of designing and building a complex geometric form. This reflects the tendency that exists in computational design practice to celebrate what Kilian describes as “the accomplishments of a geometry based computational design approach,” namely skilfully producing complex geometries and “excelling at producing images and instructions for machining and fabrication” (Kilian 2012, 45).

In this experiment, the relation of computational geometry to the geometrically enforced material through digital fabrication is that of the perfect to the imperfect. The material world is made to come as close as possible to the geometric intent. This tendency is expressed in the language of the writing itself. The written text and the descriptions struggle with precision. It points out the discrepancy between “perfect” geometry and an “imperfect” physical world, for example when feeding back the data from prototyping, reconstructing the geometric model to meet the discrepancies of material, and measuring the differences between the digital model and physical prototypes.

**Experiment 2 (Strip):**  
Extended circular and uniform exploration model

This experiment is an extension of the previous one. By introducing a manual model-making sector at the beginning of the former exploration model, the exploration model is extended to allow the designer to interact with it both intuitively and logically. The exploration begins with modelling with a paper strip, which augments the exploration with the designer’s intuitive acts and gives the designer the freedom to manipulate the material. This model is connected to the rest of the models in the chain of digital and geometrically driven design to production (Fig. 1.12).
Similar to the previous experiment, this exploration model is not neutral: it is not completely open ended, but rather already contains the designer’s intention through the selection of the paper strip as a modelling material and in the way former models are designed and connected to the CAD-geometric model. In this case, the geometric-computational model is informed by the designer’s intention through two different modes of material practice: the hand manipulation of material and the machine fabrication of material.

Experiment 3 (Hypar):
Branched, incremental, and diversified exploration model

In contrast to the previous experiments, this experiment is open ended; the exploration is treated as drifting design problem. New influences are incrementally introduced, and material effects are embraced as part of the geometric exploration (Fig. 1.13). This exploration model breaks away from seeing the exploration as only categories of models—a separate computational model containing the geometry of the intent, a structural model, a manually made material model, and a machine-made model. By loosening the categories, this experiment draws attention to the mediums of design, the bridging between them, and also the process itself, which has the capacity to form the designer’s intent and influence what the designer wants to achieve. The exploration does not involve a final idea that needs to be implemented; rather, ideation emerges from the interdependencies between mediums and the bridging of them. This experiment shows how the intent and idea evolve as the designer engages with the mediums of design in the search domain, and how the process aids in finding what designer is looking for.

In this project, geometry is used in combination with material. The process and the behaviour of the design mediums inform the designer’s intention. Consequently, the designers reform their agency throughout the process. The emphasis is on creating new features and aiding design ideation by first establishing constraints using diverse mediums and then interdependently linking them to one another. New features emerge from hybrids of diverse mediums. In this experiment, design invention includes the folded paper hypar as a design feature, folding moulds, a number of concrete and gypsum cast components, and the creation of the next experiment, the Paraboloid of One Sheet structure.
**Experiment 4 (Paraboloid of One Sheet): Parallel and bidirectional exploration model**

This experiment emerges from the previous one. It investigates the parallel exploration of multiple influences simultaneously and bidirectionally during form exploration (Fig. 1.14). It involves multiple activities in parallel and non-hierarchical interdependencies. Bidirectional links between design representations are created, allowing each of the two interdependent design representations to influence the state of the other. Since the parametric-associative system does not allow for bidirectional dependencies, this project engages designers and manually made physical models as alternatives to this limitation. In the context of parametric design, models that are controlled by the designer’s hand are only meaningful when they can interact with the digital parametric model. Consequently they must behave kinetically.

**1.6.6. Chapter 7—Conclusion and reflections**

This chapter concludes and reflects upon the results of the research and suggests future research. The finding is that in design exploration the conditions are discovered little by little through the process of design and through acts of experimentation, and design innovation occurs as unknown factors and new solutions emerge out of modelling known constraints. The creation of design is therefore a cooperation between the designer and the mediums of design. Indeed, even the formulation of the initial definition of design is accomplished by way of the designer’s expertise in the use of a particular design medium.

Finally, this thesis offers a schematic description of the new exploration model in the context of computation and digital fabrication. Algorithm as a design tool and computation as a method allow for the generation of outputs that impact the designer’s decision making, leading to the persistent reformation of the design definition, and algorithm itself is open to such reformation—the outputs of computation impact the designer’s thinking, which in turn impacts the reformation of the design set-up. As such, the design intention expands as the design expands. The new design exploration is, then, a human-medium collaboration assisted by computation. It is a combination of divergent and convergent processes that evolves over time. The designer plays a significant role in setting up the exploration in a way that allows discoveries to inform decision making throughout the design process. Thus the human designer, who has consciousness—which our current machines lack—enables a design exploration that leads to significant invention. From these experiments, two approaches to exploration are identified: goal oriented and open ended.
Design exploration using digital tools
The following brief review aims to define the position of this research in the field. It provides an overview of the origins and development of the computer-aided design tools currently in use, and the ways in which those tools have fundamentally altered design practice. It also sets out the ways in which this dissertation responds to and builds upon current research in the field, in particular with respect to the continued relevance of traditional design tools for computational design practices, the designer’s role in the design process, and the importance of using computation and prototyping as means to creative and innovative ends, rather than as ends in themselves.

2.1. Computer-aided design (CAD) for design exploration

Design is a complex task that is performed by humans. Computer-aided design (CAD) tools and their affiliated computational technologies have been developed to assist designers in exploring design alternatives. Though there are several excellent general reviews of development of CAD tools and computational technologies in architecture, each to some extent reflects its author’s personal research interests and view of the field. Moreover, due to the pace of development and breadth of research, a truly comprehensive review is probably impossible, and in any case is beyond the scope of this dissertation. To position this research with respect to the use of CAD tools in design exploration, it is sufficient to present three trajectories of the early development of CAD in relation to intentions and values. These trajectories are adapted and developed from Jonas Runberger’s dissertation “Architectural Prototypes II: Reformations, Speculations and Strategies in the Digital Design Field” (Runberger 2012, 12). The intention of presenting these trajectories as discrete paths is not to separate their development, but rather to highlight the ways in which the different values of the trajectories can lead to very different approaches in tool development, which eventually impacts the way designers can explore with them. The three trajectories can be summarised as follows:

- the use of CAD as a digital representation of the building process to control the flow of information in a rational way, improve efficient communication, and facilitate a change in the overall construction process;
- the use of CAD as a tool that impacts design sequences for the exploration of form and architectural effect through formation processes;
- the use of CAD with an interest in form-finding and optimization, combined with computer-aided engineering (CAE) tools. It is the use of CAE that impacts how we analyse, generate, and produce architecture.
The first trajectory is the use of computers for the digital representation of the building process in order to facilitate the exchange and use of information in a digital format. This line of development has been presented under different names: Building Information Modeling/BIM by Autodesk, Virtual Building/VB by Graphisoft, and Integrated Project Models/IPM by Bentley Systems. The overall objective of this trajectory has been “to control the flow of information in a more rational way, to improve efficient communication and facilitate a change of the overall construction process” (Runberger 2012, 12). An important aspect of CAD development in this trajectory has been to allow architects and engineers to store large numbers of datasets within the building model. Eddy Krygiel and Bradley Nies define BIM as “the creation and use of coordinated, consistent, computable information about a building project in design—parametric information used for design decision making, production of high-quality construction documents, prediction of building performance, cost estimating, and construction planning” (Krygiel and Nies 2008, 27).

Without a doubt, the idea of this trajectory has its roots in the “crisis of control” of the information society from the second industrial revolution (Aghaei Meibodi 2012a, 22–23). Thus, it has aimed at managing, processing, and sharing information. One of the first instances of CAD development aligned with this trajectory was ArchiCAD. Introduced between 1982 and 1987 by Graphisoft, it marks the beginning of this trajectory for architecture. (Another well-known example, Revit, was developed between 1997 and 2000 by Revit Technology Corporation.) In the 1980s, most architecture school curriculums included 2D CAD drawing, and ArchiCAD was taught in computer classes parallel to the design studios; however, few students used the computer for their designs. For architecture students, the typical problem with using the CAD products that emerged from this trajectory innovatively was the rigid, factory-set limitation of the predefined 3D objects used to create walls, floors, roofs, structure, windows, doors, and other objects—all of which followed the post and beam system of industrial building production (Fig. 2.1).

The software developed for BIM was the first to maintain the geometric consistency and integrity of the building model in spite of any changes or modifications that may have been made to it later. This capability is known as parametric modelling. In this kind of software, the objects are defined as parametric objects consisting of a series of geometric definitions and associated data and rules. These geometric definitions are integrated non-redundantly and do not allow inconsistencies between the model and its associated dataset. This means that any changes made directly to the model will result in an equivalent change to the dataset associated with the model (Eastman et al. 2011, 31–97).
The second trajectory, which is central to this dissertation, emerged in the 1990s. It is the integration of CAD into architectural design processes with an interest in producing complex geometry and topology. Initially, the limitations and potentials of 3D modelling programs were studied and pushed to explore new architectural forms and effects in terms of their formation processes. The beginning of this trajectory is associated with the creation of the “paperless studio” at Columbia University—design studios immersed in digital technologies. Columbia’s School of Architecture was one of the first to notice the inefficiency of having computer classes as a separate entity from design studios, and the first to fully integrate digital technology into its architecture studio: “Initially, CAD courses did little more than facilitate the production of architectural drawings and did not have much impact on the all-important Design Sequence. By the early 1990s, remarkable advancements in two commercial 3-D modelling software packages, Alias/Wavefront and Softimage, offered revolutionary possibilities for architectural design” (Rashid n.d.).

The use of Alias and Softimage in the film industry to create complex 3D special effects attracted the architects of the time. This software offered “toolsets, including NURBS (Non-Uniform Rational Basis Splines), which allowed designers to model accurately forms with complex 3-D curvatures and surfaces, and 3-D Booleans, which permitted 3-D addition and subtraction of space, a process that resembles modelling clay” (Rashid n.d.). From exploring and testing the limitations of this software, “a radically different kind of architecture emerged. Designs from the first few years of the paperless studio often look like the permutations of an amoeba and feature complex, amorphous geometry that is not reducible to the elementary...
Indeed, the initial use of the computer in the direction taken by the pioneers of the second trajectory may be seen as instrumental in supporting continuity and curvilinearity in architecture. For example, the works that Greg Lynn refers to as “blobs” promoted a new architecture of biomorphic forms. However, in the mid-1990s and onwards, the computer became an essential tool for the exploration of these concepts in architecture.

Blob is an acronym for “binary large object.” See Greg Lynn, “Folds, Bodies and Blobs: Collected Essays” (La Lettre Volee, 1998), 158-169 and “Blobs,” in Journal of Philosophy and the Visual Arts 6 (1995): 39-44. The early works in this trajectory were also heavily influenced by Deleuze’s concept of the fold, which he developed by reconstructing Leibniz’s metaphysics, the role of infinitesimal calculus, and the law of continuity; see Gilles Deleuze, “The Fold—Leibniz and the Baroque: The Pleats of Matter,” Architectural Design Profile No. 102: Folding in Architecture (1993): 17–21. For architects of the time, the fold was a way to envisage complexity in terms other than of the discontinuity and frontal collision that was offered by deconstructive architecture. These ideas were theorised in 1993’s Architectural Design Profile No. 102: Folding in Architecture, edited by Greg Lynn.

18. Alias/Wavefront, which was initially developed for the automobile industry to model complex car parts, was used to create the water effects in the 1989 film The Abyss. The dinosaurs in the 1993 film Jurassic Park were created with Softimage. Using these tools, much of the early work in this trajectory was either visualization or formal speculation. Many of the practitioners in the paperless studio could not see themselves in the building industry and have therefore continued their careers in other industries like film. See, for example, the interview with Joseph Kosinski at the 5D Conference (“5D Conference : Narrating Space Pt 4 - Joseph Kosinski” 2010).

19. This kind of software enabled clay-like modelling. For a description of NURBS, see the author’s “Manifested in Form: Tension between Utility and Form in the Digital Design of Architecture” (licentiate book, LTU, 2012), 36, 45.

20. Alias is the forerunner of today’s Maya.
The third trajectory, which is rooted in a cybernetic approach, is defined by Runberger as “an interest in computational processes, and the way they can change our way to analyze, generate and produce architecture” (Runberger 2012, 12). Cybernetics is the study and optimization of systems, or, as Norbert Wiener defined it in 1948, the science of “control and communication in the animal and the machine” (Weiner 1948). An example of such a control and communication system can be seen in humans: in order for the hand to lift a piece of broken glass without injury, the lifting force used is regulated through a communication and control feedback loop between the brain and the “the science of control and communications in the animal and the machine” sensitive nerves of the fingers.

CAE analytical and simulation software aimed at optimization belongs to this trajectory. Simulation is the abstraction and representation of the behaviour of real-world systems and processes over time. Models are used to do this: while the model represents the real-world system and condition itself, simulation abstractly replicates its behaviour over time. The use of the computer in this trajectory has mostly been for the optimization of structure, form, material, and behaviour.

Over the last decade, many ideas, such as the interest in form-finding using CAD, have blurred the boundary between the second and third trajectories. In a number of projects, we see that instead of using constraints and forces to post-analyse the form, constraints and forces are modelled with a ruleset (regulatory system) to create the form (Fig. 2.3). This is also known as simulation-driven design: by creating links and feedback loops between the computational geometric CAD and CAE analytical models, the designer can explore design alternatives with respect to their real-world context. The interest in simulation-driven design can be traced to pre-digital architects such as Gaudí and Otto, whose work is associated with an interest in form-finding.
The Finite Element Method (FEM) for material behaviour and Computational Fluid Dynamics (CFD) for fluid and gas behaviours are examples of this kind of CAE software. Contemporary projects in architecture that can be categorized as belonging to this trajectory include those involving artificial intelligence, optimization, complex adaptive systems, cellular automation, simulation, patterns and organization, genetic algorithms, swarm intelligence, and self-organizing systems. Concepts like learning, adaptation, emergence, communication, efficacy, and interconnectivity are also connected to this trajectory.

As noted by Runberger, “digital design processes, data management and a prototypical approach to development must be related to the discourses of architecture and the concept that drive design,” and “discourses of architecture are dependent on the technologies employed within design and processes” (Runberger 2012, 12).

Understanding the values of each trajectory is important, as those values have driven the ways that CAD and its affiliated computational technologies are used, which in turn impact the direction of their further development. The research carried out in this dissertation has its foundation in the second trajectory and employs the third trajectory in its direction. This is not to overlook CAD development in the first trajectory, but rather to focus on the design sequence and the tools that enhance design processes and the design exploration to examine computational techniques that impact design processes and the designer’s ways of exploring design as well as analysing, generating, and producing architecture.

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21. The Finite Element Method (FEM) for material behaviour and Computational Fluid Dynamics (CFD) for fluid and gas behaviours are examples of this kind of CAE software.

22. Contemporary projects in architecture that can be categorized as belonging to this trajectory include those involving artificial intelligence, optimization, complex adaptive systems, cellular automation, simulation, patterns and organization, genetic algorithms, swarm intelligence, and self-organizing systems. Concepts like learning, adaptation, emergence, communication, efficacy, and interconnectivity are also connected to this trajectory.

23. As noted by Runberger, “digital design processes, data management and a prototypical approach to development must be related to the discourses of architecture and the concept that drive design,” and “discourses of architecture are dependent on the technologies employed within design and processes” (Runberger 2012, 12).
2.2. Parametric-associative system and algorithm for CAD

In the second trajectory, the later developments of the parametric-associative system and algorithmic environment in CAD and 3D modelling software have changed the role of the computer in design: it has gone from being a tool that enables the creation of what the designer already has in mind to a tool that allows the designer to explore design through computation. Initially, the use of CAD software in this trajectory was based on conventional mouse-based manipulations of digital instants, such as control points on NURBS curves, NURBS-based surfaces, mesh surfaces, and so on. Basically, the use of the computer was limited to mouse-based drawing, 3D modelling, and the modifications and operations offered by available CAD software, limiting its application to the realisation of the designer's intentions. However, as Kostas Terzidis points out, "mouse-based manipulations of 3D computer models are not necessarily acts of computation" (Terzidis 2006, xi–xii). While mouse-based manipulation involves extensive back-end computation, "the rearrangement of . . . control points through commercial software is simply an affine transformation, i.e. a translation" (Terzidis 2006, xi–xii).

There is a great difference between tools for realising what is already determined, and explorative tools that allow the designer to discover new possibilities. Today the computer is a computational tool for exploration, enabling computation in design and human-machine collaboration. This fundamental change in the role of the computer in design has given rise to the discipline of computational design and to computational methods in architecture. Coenders writes that "computational design attempts to support the process of design by providing concepts, guidelines and computational strategies to appropriate existing and new technology for (structural) design. Computational technology is strong in storing and processing large amounts of data in a fraction of the speed of human labour" (Coenders 2010, 589). As a result, digital computing outcomes exceed human visualisation capabilities.

The parametric-associative system, which has been around since 1989 (Shea, Aish, and Gourtovaia 2003, 554), supports computational design and the use of computation in design exploration. Software equipped with this system provides designers with design environments in which they can define the generic properties of a 3D geometric model within a user-defined framework; in this framework, relationships between geometric parts of a form are explicitly defined, the interdependencies between the various geometric instances (line, curve, etc.) are established, and instead of directly manipulating these digital instances, different values are assigned to them. Once the generic properties of a geometric model are defined, the designer can easily generate a complex nonstandard form and explore multiple variations of it by varying the parameters “while maintaining [the] conditions of the topological relationship” (Mitchell 2009, 12).

The parametric-associative system supports design exploration by enabling the designer to create parametric models that are easy to modify after they are created, thus “[providing] designers and their clients with an enhanced ability to explore ranges of variants on design concepts” (Mitchell 2009, xvii). It allows a parent-child relationship between parts of a geometric form, and keeps track of how the geometric model is constructed. For instance, an array of curves can be used to create a surface, and the software remembers from which set of curves the surface is composed. Later in the project the designer can go back to an earlier step and change the initial curves that the surface is built from, and the changes will propagate through the geometric association—thus the output—surface—keeps up with the changes. This function enables the designer to go back to earlier steps and create changes at any time throughout the design process, while being assured that the changes will propa-
Parametric modelling itself is not a new concept: already in the 1960s it was a feature of the CAD program Sketchpad, designed by Ivan Sutherland. However it was not until recently that its availability to designers through various CAD programs made it a common tool in architectural design (Davis 2013, 207). “Parametric modeling as a concept and mathematical construct, e.g. parametric curves and surfaces, has been around for years with the first parametric CAD tools emerging in 1989” (Shea, Aish, and Gourtovaia 2003, 554).

As Kostas Terzidis points out, “a designer/architect’s creativity is limited by the very programs” available. “There is a finite amount of ideas that a brain can imagine or produce by using a CAD application. If a designer/architect doesn’t find the tool/icon that they want they just can’t translate that idea into form” (Terzidis 2006, 155) It should be point out that while the author agrees with Terzidis that finding the right tool is important, the author is critical of his view on simplifying the application of CAD for translating idea to form. The author sees the potential of the new computational tools offered by CAD in their capacity for reforming designer’s intentions.

Instead of being used to draw what the designer already has in mind, the computer is used for ideation and the exploration of unknown design outcomes.

A parametric and associative computational design system is one that allows computation: processing information. GC was developed by Robert Aish for Bentley. It was introduced in 2003 and has been employed in practice since 2005. Axel Kilian discusses GC in his dissertation (Kilian 2006, 50). Kilian has co-taught workshops in the Smart Geometry Group since 2003, and Smart Geometry was an important community for progress in the development of GC. In Smart Geometry’s annual workshop, GC was tested and its developers received feedback from users (the author was introduced to a beta version of this software in 2005–06).

Software equipped with the parametric-associative system enables the designer to work both “strategically” and “intuitively” (Shea, Aish, and Gourtovaia 2003, 554). Citing Peter Szalapaj’s book “CAD Principles for Architectural Design,” Shea, Aish, and Gourtovaia note that “parametric modelling involves the use of geometric constraints as well as dimensional relations and data to drive shape definition.” In such a model the “values within parametric expressions can be modified by designers and are then propagated through the design, i.e. strategic manipulation. Alternatively, associative geometry allows dynamic manipulation of user-defined dependency relations by graphical manipulation, i.e. intuitive manipulation” (Shea, Aish, and Gourtovaia 2003, 554). Parametric software “links dimensions and parameters to geometry and thereby allowing for the incremental adjustment of a part which then affects the whole assembly” (Leach 2010, 8). However, Rick Smith, a CATIA expert, criticizes the parametric-associative system for its rigidity and the unpleasant consequences of preformulation. He notes that “when you model using parametric you are programming following similar logic and procedural steps as you would in software programming. You first have to conceptualize what it is you’re going to model in advance and its logic. You then program, debug and test all the possible ramifications where the parametric program might fail. In doing so you may over constrain or find that you need to adjust the program or begin programming all over again because you have taken the wrong approach” (Smith 2007, 2).

The factory-set interface of GC constrained the designer’s direct interaction with the generic properties that would generate the 3D geometric form; it did not enable the designer to move freely and work with the generic properties and the definition that outputs the 3D geometric form. GC has a symbol window that embeds a representational graph linked
with the 3D geometric form: this graph is not exactly the definition of the geometric form, but only a representation of parent-child relationships, representing connections between components (Fig. 2.4). While the interface allowed the designer to interact with the graph to some degree, this interaction was very limited. One would not use the graph as a tool to arrive at the 3D geometric form; rather, the symbolic graph was a representation for the designer to observe the parent-child relations.

The limitations imposed by the factory-set interfaces of 3D modelling software, combined with growing interest in computational procedures for formal exploration, renewed interest in using scripting and programming in architectural design. This in turn led to the use of algorithm as a tool for design exploration, as discussed in the following chapter. Using the scripting interfaces embedded in 3D/CAD modelling software (examples include 3D Max Script, Maya Embedded Language [MEL], Visual Basic and Python in Rhino, Processing [Java], and GC Script in Generative Components), the designer is able to freely and directly express the generic parametric definition and the parametric values and relations of a 3D geometric model. This means that by describing sets of instructions the designer can specify the parameters and associations. Thus the parametric-associative model is created by describing the set of rules and definitions, rather than by interacting with a fixed, factory-set interface. This set of rules and definitions is an algorithm. Leach notes that “within the field of digital design, [algorithm] refers to the use of scripting languages that allow the designer to step beyond the limitation of user interface, and to design through the direct manipulation not of form but of code” (Leach 2010, 9). Through a scripting environment, the designer works directly with the script of a 3D geometric form.
geometric model and designs freely, interacting with and interpolating the definition of the 3D geometric form independent of a factory-set interface.

For designers not versed in programming or scripting, there are algorithmic environments based on graphical algorithm editors. Grasshopper, for example, is commonly used in architecture schools and is tightly integrated with Rhino’s 3D modelling software. It is a graphical interface that allows the user to easily move around the structure and definition of the geometric construct. In general, Grasshopper is based on Visual programming language, a language that enables the designer to create a program by manipulating the program elements graphically rather than by specifying them as script. It allows designers to work with algorithm in form of the Grasshopper definition, which is built of “components.” In Grasshopper, a component is a built-in block that performs a particular action, for instance a component that generates a curve from three points. It computes as a “black box,” meaning the designer doesn’t have to know how it works, but only needs to know the input and output of the component. In the given example, three points (inputs) are needed to get an output (curve) (Fig. 2.5). Similar to earlier parametric platforms, Grasshopper is capable of keeping track of the history of the geometric parent-child associations. In this case, the associative and parametric modelling system is embedded in the definition (it is the designer who embeds them in the definition by linking the components to one another). Compared to scripting and programming, Grasshopper is a more constrained environment in which to express the definition—generic properties—of a geometric form.

Figure 2.5. The Grasshopper definition consists of a set of inputs—linkages of components that are connected to one another following the parent-child relationship of the parametric-associative system. Grasshopper uses the Rhino viewport to display the geometry. In order to pass data through the definition from one component to another, connecting wires are used to connect the output of one component with the input of another.
While using Grasshopper, scripting, and programming, designers go beyond the limitations of manipulating digital instances manually with the mouse: working with scripting and programming frees the designer to a large extent from the factory-set limitations of software interfaces. In his publication “No Silver Bullet,” Fredrick P. Brooks, Jr. goes through the problems with Visual programming, for example, to state why, in the end, there is nothing to do but get one’s hands dirty and program (Brooks 1986, 1-16). However, Grasshopper and scripting both involve the designer using “software programs to generate space and form from . . . rule-based logic” (Terzidis 2006, xii). For this reason, working with any of them involves the designer in designing algorithms (described in the next chapter) and in a procedural activity that uses the algorithmic method. This research therefore generalizes and refers to both as “algorithm.” In this dissertation, to examine the potentials and limitations of computation and computational techniques for design exploration, Grasshopper is used in the experiments most often, and the Python and Visual Basic scripting within Rhinoceros are used when necessary.

Today, this line of development—the use of the parametric-associative system and algorithmic procedure for design exploration—has several branches focusing on a variety of subjects. Central to this dissertation is fabrication-driven design in architecture, in which the interest is in integrating digital fabrication tools into the design process and experimenting with them to explore architectural potential.

2.3. Integrative design

The possibility of aligning the analytical simulation tools of the third trajectory, the second trajectory’s concern with design exploration, and digital fabrication tools in the exploration of form and architectural potential has led to the emergence of integral design-to-production processes and a new interest in architecture as material practice.

The introduction of the computer into design and production processes came with the development of CAD software in the 1960s and CNC machinery in the 1970s (Harp 1985, 61-63). Eventually, the computer-aided design and computer-aided manufacturing system (CAD/CAM) was developed, which enabled CAD software to communicate directly with CNC machining tools (Harp 1985, 61-63; Fig. 2.5), introducing a direct link between the design and manufacturing stages in CAD/CAM-based design and production processes. This link, which has been established through digital technologies, is described by Branko Kolarevic as “a new digital continuum, a direct link from design through to construction technologies” (Kolarevic 2003c, 2). This link created new opportunities for the practice and profession of architecture “by allowing production and construction of very complex forms that were, until recently, very difficult and expensive to design, produce and assemble using traditional construction technologies” (Kolarevic 2003c, 2).
Figure 2.6. A simplified schematic illustration of the CAD/CAM system. Adopted from Levary’s simplified schematic illustration of numerically controlled (NC) machine (Levary 1995, 215). With the CAD/CAM system, the designer is able to produce instructions for the fabrication of parts.

Moreover, the introduction of the computer in related disciplines, such as structural engineering and environmental engineering, through the development of computer-aided engineering (CAE) simulation/analytical software (e.g., software for structural analysis) enabled engineers to simulate real-world situations in the future building context. The integration of CAE and CAD software enabled designers to predict building performance in the real world prior to physical construction, which further supported the design-to-production process. Once engineers and architects were able to model their tasks using digital tools that themselves use 0s and 1s as their primitive data, a common ground between the two disciplines was created—information as a common ground (Aghaei Meibodi 2012b, 108). Once these models could communicate with one another, they were developed and used interdependently. Using a feedback loop, data from other disciplines are input in the early design stage and used to change the design, incorporating factors such as climate or fabrication constraints in the early design processes (Fig. 2.7).

Figure 2.7. Creating direct links and a feedback loop between the CAD computational geometric model and CAE computational analytical models. The CAE analytical model is used in a generative manner to drive the geometry and topology in the geometric model.


34. For more on the concept of the digital continuum—the direct digital exchange of information across different disciplines—see Branko Kolarevic, Architecture in the Digital Age: Design and Manufacturing (Routledge: Taylor & Francis, 2003), 58–59. It is important to note that this link is much smoother and more direct in theory than it is in practice.
In the development of the parametric-associative system and algorithmic procedure for computation, computation power and the communication links between different expert software programs has enabled the cooperation between CAD, CAE, and CAM processes (Fig. 2.8), giving birth to the collaborative design and engineering procedure, and “Integrative Design” discussion in the computational design field (Kolarevic 2008, 339). As noted by Kolarevic, computational methods enable highly collaborative and highly integral design, engineering, fabrication, and construction procedures (Kolarevic and Klinger 2008, 6–7; Kolarevic 2008, 149; Kolarevic 2009, 338–339). Oliver Tessmans’s dissertation “Collaborative Design Procedures for Architects and Engineers” describes a number of ways in which algorithmic procedures are utilized to improve the interface of both structural engineering and architectural design for collaboration between the two disciplines (Tessmann 2008).

As Kolarevic notes, “The ability to digitally generate and analyse the design information, and then use it directly to manufacture and construct a building fundamentally redefines the relationship between conception and production—it provides for an informational continuum from design to construction. New synergies in architecture, engineering and construction start to emerge because of the use of digital technologies across the boundaries of various professions” (Kolarevic 2003d, 59). Moreover, linking the output of this design to construction continuum with its input in a circular fashion—a feedback loop—the conception is reformed and augmented: the continuous flow of information is a comprehensive continuum that provides useful information and knowledge in the process of creating complex form. Working in this way, the designer must be prepared to learn from what comes out of the latter stages of design and create informative feedback loops.

Figure 2.8. Cooperation between the CAD, CAE, and CAM processes gives rise to an informational digital continuum from design to production. The syntheses of the results are fed back to the CAD-geometric model to reform the design concept.
2.4. Revival of architecture as material practice

While the use of digital fabrication technologies was initially associated with automation and production in the final stages of design (Oxman 2012, 427), in the last fifteen years the availability of generic CNC machinery and robot arms in architecture schools has revived notions of craft, making, and manufacturing in the architectural design process. As a consequence, designers have experimented and become directly involved with the tools and techniques of materialization in the conception of design as well in actual production. This is illustrated in Kolarevic’s Architecture in the Digital Age: Design and Manufacturing as well as Kolarevic and Klinger’s Manufacturing Material Effects: Rethinking Design and Making in Architecture (Kolarevic 2003d; Kolarevic and Klinger 2008). Kolarevic and Klinger note that “the new techniques and methods of digitally-enabled making are reaffirming the long forgotten notions of craft, resulting from a desire to extract intrinsic qualities of material and deploy them for particular effect. As such, interrogating materiality is fundamental to new attitudes towards achieving design intent,” adding parenthetically that “after all, architecture is fundamentally a material practice” (Kolarevic and Klinger 2008, 7). Indeed, “digital fabrication shifts material thinking into the core of design intention,” connecting “the descriptive practices of design and the material practice of fabrication” and “[shifting] manufacture from a practice-based knowledge residing with the craftsman, to an integrated practice that interfaces with all the different disciplines in the design chain” (Thomsen et al. 2013, 9).

New material practice is shaped by the particular way that digital fabrication tools are used in architecture. Design becomes an interface between the conventional descriptive and theoretical design domain of architects and the conventional empirical production domains of manufacturers (Thomsen et al. 2013, 8). In this regard, “rather than perceiving the material realization of design objects or buildings as something that takes place after design, planning and optimization,” materiality and ways of working and thinking about material are central to the design process (Thomsen et al. 2013, 9).

Both the design process and the realization of the design idea itself involve material thinking and making as a way of working and thinking about design (Fig. 2.9). By designing, we connect conventional descriptive thinking in design with material thinking.

In addition to intensifying the relation between design and making—between the design process and the realisation of the design idea—the availability of digital fabrication tools in architecture schools has led to the production of many full-scale prototypes both in the course of design and at the end of the design process. The temporary large-scale prototypes produced by the Institute for Computational Design (ICD) and the Institute of Building Structures and Structural Design (ITKE) in Stuttgart, Germany are

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35. This integration is not a closed system, as promoted by BIM; as Kolarevic suggests, we must “avoid closed systems of integration and to keep integrative tendencies as open as possible, conceptually and operationally” (Kolarevic 2008, 654).
examples: designed and constructed to explore material effect as part of a computational design process, these structures in the form of pavilions are used to explore and demonstrate the latest developments in material- and making-oriented computational design, simulation, and production processes in architecture (Menges 2014).

2.5. Integral computation and materialisation for design exploration

Architecture, as a material practice, attains social, cultural and ecological relevance through the articulation of material arrangements and structures. Thus the way we conceptualize these material interventions and, in this context particularly the technology that enables their construction, presents a fundamental aspect in how we (re)think architecture. —Achim Menges (Menges 2013, 196)

The advancement in computational technologies for CAD—specifically in the parametric-associative system and algorithmic environments for architects (interfaces as well as coding, scripting, and programming environments)—has moved the role of digital production tools and prototyping beyond merely enabling the building and testing of geometrically complex forms. Instead of implementing a material construct to realise a design idea, the material construct has become an essential part of the design process and even the initial creation of design ideas. Today, prototypes and pavilions are built integrally, using computational design processes to explore new articulations of material arrangements and structures, drawing upon the intrinsic qualities of materials and of fabrication and assembly logic for particular effect in the conception stage of design. This approach, in which the subsequent stages of design to production can take part in both the conception of a design and the realisation of a design idea, has been referred to as “integral formation and materialization” (Menges 2008, 196) or “integral form generation and materialization” (Menges 2007, 726).

As the last output devices in the digital design-to-production process, generic CNC machinery and robot arms are the interface between digital information models and the physical, materialised artefacts of those models—between the virtual formation stage and the materialization stage (Fig. 2.10). Integral formation and materialization involves considering aspects of materialisation much earlier in the design process and making them essential to conception as design drivers. Such an approach intensifies the relation between conception and materialisation at the early design stages. In such an approach “the concept of material systems” (Menges 2007, 726) is extended to the early design stage. By enabling designers to embed “material characteristics, geometric behaviour, manufacturing constraints and assembly logics within integral computational models” this approach “promotes an understanding of form, material and structure not as separate elements” (Menges 2007, 726) but as integrated.

Fabio Gramazio and Mathias Kohler argue that despite the rapid adoption of digital fabrication technologies and the common practice of prototyping, the exploration of architectural operability is slow and the potential of these technologies for architectural practice has not been fully explored: “there are still experts needed who can ‘solve the problems’ of transforming the designed digital models into built reality” (Gramazio, Kohler, and Langenberg 2014, 6). An example of such expertise can be found in the design consultancy firm Design-Toproduction, which has specialised in solving the digital production of complex designs. They note that “to make the full spectrum of digital technologies in architecture accessible, to unfold it or even exhaust it, they have to be considered conceptually in design from the very beginning” (Gramazio, Kohler, and Langenberg 2014, 6).
With this in mind, the question is no longer whether or not a particular so-called complex form is buildable, but rather how can materiality be made integral to the conception of a design idea at the early stages, and to what extent does it augment the formation of the design idea, the exploration, and the product. Gramazio and Kohler point out that with recent developments in digital design techniques and fabrication technology “the design incorporates the idea and knowledge of its production already at its moment of conception. In turn, the understanding of construction as an integral part of architectural design takes on greater significance” (Gramazio and Kohler 2008, 8). For the author, the larger challenge is to conceptualise potentials and constraints in such a way that they are fruitful and augment ideation itself, the exploration, and the articulation of complex forms.36

The algorithm plays an important role in enabling designers to “[synthesize] computation and materialization in one integral process” (Menges 2010, 1). The algorithm as a design medium and as a means for conceptualising the constraints and potentials of materiality plays an important role in enabling such a conception of the design idea. In most of their work, Gramazio and Kohler demonstrate how design, fabrication, construction, and assembly can be integrated directly in a single design process from the conception stage onwards by using scripting and programming languages (Gramazio, Kohler, and Oesterle 2010, 111). Using the algorithmic tools available in CAD software, they encode the assembly logic of material systems and the logic of CNC machinery capable of carrying out different actions of fabrication and assembly in the real world. However, the questions that arise are, do the ideas already exist clearly at the early stage of design? are the constraints of materialisation already known at this early stage? and how do the characteristics of the design mediums and tools impact ideation, the designer’s intention, and the exploration model?

With recent advances in CAD software placing parametric-associative and algorithmic technology at the designer’s disposal, the subsequent stages of design to production—fabrication, construction, and assembly—as well as the capacities of construction materials can take part in the conception of design and the realisation of a design idea. However, these computational technologies have done more than enable the conceptualisation of

36. “Complex forms” being forms that are not easily describable with Euclidian geometry, or are not reducible to a known shape.
construction material, fabrication, construction and assembly steps at early design stages—they have also given rise to a generative approach to the design process.

2.6. Generative approach to design exploration

With the development of scripting environments and node-based graphical algorithmic interfaces for designers and architects, generative methodologies based on the associative-parametric concept and the concept of algorithm for processing information have been introduced to architectural design. A new approach to design, the computer-aided generative design process, has become common and significant in the architecture of the present.

The terms computational design and generative approach, which are commonly used in relation to the second trajectory, are relatively new and need some clarification. To the author, “computation” refers to the processing of information—it does not necessarily lead to generating outcomes; it is the term “generative” that points to the character of a design process in which outputs are automatically generated. Therefore, computation and computational methods can be used to enable a generative approach to the process of design exploration.37

This approach uses computational methods to automatically generate design outputs, enabling the designer to test ideas quickly with many alternatives, saving time. This approach to design deals with creation of outputs (images, geometric forms, etc.) by using sets of computable rules and procedures (Bohnacker et al. 2012, 460). It has been noted that in such an approach “an image is no more created manually but through a visual idea which is translated into a set of rules and then implemented in a programming language in the form of source code. The consequence is that such a program can not only create a single image but also completely re-design visual worlds by changing the parameters” (Bohnacker et al. 2014) using accessible programming, scripting languages, or algorithmic graphical interfaces.

The design tools that have enabled the proliferation of the computer-aided generative approach are the scripting environments and algorithmic graphical interfaces in current CAD software. Today, most CAD programs allow for scripting or have node-based graphical algorithmic interfaces, which enable the designer to describe design intention in form of procedures and rules, and to make subsequent changes to geometric properties and other attributes according to the parameters that are changed. Through their links to fabrication and construction tools, CAD-algorithmic tools have enabled “changes [in] the culture of architecture, both in its expression and in its productive capacity” (Gramazio and Kohler 2008, 9). Using digital logic relationships and intentions are defined in the form of rules (Gramazio and Kohler 2008, 10).38

2.7. Role of digital tools for ideation

The contemporary theoretical case celebrates the use of computation for integrating different aspects of a building project and connecting the design exploration with the real-world context of building. This chapter shows that by synergising tools across the building disciplines, designers can have an “integrative design” process (Kolarevic 2008, 656) in which form is generated with reference to the constraints of its future site or production context. In integrative design, digital technologies are used to link computational analytical models to computational geometric models generatively and as “an enabling apparatus that directly
integrates conception and production” (Kolarevic 2003c, 3). Integration is achieved with an emphasis on digital continuity and conformity between different aspects of a building project. Does such a purification of the design limit the designer’s experience and ultimately the creative exploration?

The progress of computational power and algorithmic tools towards the possibility of creating “a direct link from design through to construction technologies” (Kolarevic 2003c, 2) is celebrated in the design and production of geometrically complex forms which “were, until recently, very difficult and expensive to design, produce and assemble using traditional construction technology” (Kolarevic 2003c, 2). However, in such projects there is an overall lack of discussion about the role of design mediums in relation to the designer and to design itself beyond enabling the building of complex geometry. As Kilian has also pointed out, “the desire to celebrate the accomplishments of a geometry based computational design approach excelling at producing images and instructions for machining and fabrication is understandable but looking at the computational design challenge overall the gap in contributions to the conceptual realm is very large and rarely discussed” (Kilian 2012, 45). What is the role of digital tools for ideation? To be precise, are these just tools to realise preformulated ideas, or can they support the designer in the process of ideation?

Today, as a result of the designer’s access to digital fabrication tools in the course of a design exploration, the experiment with form is carried out in a hybrid digital and physical environment. Full-scale prototyping has become an integral part of the exploration. The process of integral computation and materialisation has become established, and algorithms and the parametric-associative system play significant roles in enabling this. Gramazio and Kohler note that, using digital logic, relationships and intentions are defined in the form of rules (Gramazio and Kohler 2008, 10).

It is presented that algorithm allows for the incorporation of fabrication, construction, and assembly knowledge into the conceptual stage of design, as well as the reformation of the CAD-geometric model in every cycle of design to production. But there remain a few open questions: is the algorithm, in and of itself, enough to formalise designs completely? to enable a creative exploration, is it enough to only design an algorithm that encodes the constraints? As Gramazio and Kohler ask, “does it make sense to formalize designs completely or partially in computer programs, to write down architectural logics, instead of drawing or modelling architectural forms” (Gramazio and Kohler 2008, 8)? Considering the designer’s mode of operation and design as a “process of active choice” (Shelden 2014a), can the exploration be limited to only numerical and algorithmic (rule-based) means? The roles of the designer and design as enablers are little discussed in the literature, and the use of the hand is lost in current digital computational design and materialisation processes. Can design be reduced to merely conceptualising constraints and carrying out a predictable workflow—that is, to “the execution of established processes” (Kilian 2012, 44)? To be specific, can the realisation of the design and ideation be reduced to only the implementation of the material construct—the building part—as the fabrication influences the design and vice versa? Is
it even possible to conceptualise all the constraints immediately at the early design stage? What role do digital tools play in design ideation? How can we use computation and digital fabrication tools to augment the designer’s experience and consequently aid ideation and novel exploration?

In the following chapters, this dissertation embraces and examines the idea of employing logic and programming language for conceptualising knowledge related to the materialisation stage—turning constraints to integral drivers in the design. It also augments this thinking and promotes other ways of conceptualisation besides pure logic of algorithmic formalisation and numerical formalisation. There are other means of conceptualisation beyond the numerical that can work interdependently with the numerical mode to enable a creative exploration; this dissertation identifies algorithm, geometry, and material as three mediums for design and suggests augmenting the exploration model by means of cooperation among different design mediums and the designer.
Algorithm:
Logical design medium
Since the late twentieth century, there has been a shift in the way architects have used digital design and fabrication technologies. Computational advances in 3D modelling software—the parametric-associative system and the common use of algorithms—and the widespread availability of generic CNC machinery and robot arms in architecture schools have combined to push digital design and fabrication beyond merely enabling a digital continuum of design to production with the intention of producing a complex forms or enabling collaborative and integral processes for building projects. As the new computational tools have developed, there has been a growing interest in incorporating knowledge of manufacturing, material capacity, and site conditions into the design exploration as drivers for generating design ideas.

The algorithm has been used in architecture as a form-generation tool that enables this incorporation. It is generally said that the algorithm overcomes the limitations of traditional CAD tools and also helps the designer to work beyond geometry and three-dimensional space. It offers the designer the possibility of incorporating disparate knowledge from a variety of disciplines into the design exploration in order to generate a spectrum of forms and possibilities to choose from in proceeding with the design. The algorithm can be seen as an abstract machine, in that its application in CAD and 3D modelling software enables computation and the incorporation of computational techniques in architectural design exploration. In fact, in the research that is presented here, the algorithm is a basis for practicing computation and integration in the field of computational design in architecture as material practice.

This chapter attempts to present the major inherent characteristics of algorithm with respect to the nature of design processes. It looks at its potential and limitations for design exploration in the context of architecture as material practice—for example its capacity for conceptually integrating constraints and potentials related to digital fabrication tools and methods—and for supporting material thinking and making as part of design exploration. Moreover, a number of ways that algorithm has been used in architecture with respect to material practice are presented. The intention of this research is not to dictate what algorithms should be used for in architectural design, nor to demonstrate how to employ them in a CAD environment to perform basic calculations. Rather, it investigates whether or not computational methods alone are sufficient to enable designers to explore, to drive design, and to conceptually integrate the constraints of materialisation at the early design stage with the purpose of turning them into design drivers. It further investigates the impact of the use of algorithm on the ideation of the design idea. Algorithm may be seen as an abstract machine that enables computation in design through virtual formation.
3.1. The concept of algorithm

The concept of algorithm can be seen as a goal-based method for performing a task. Generally speaking, an algorithm is a set of precisely defined instructions or rules to be followed: a procedural, step-by-step way to describe a series of actions to be performed in order to achieve a particular goal such as solving a problem or searching for something. The instructions define a sequence of operations, and are not always used for numerical calculations. For instance, a set of instructions for making tea can be seen as a tea-making algorithm (Fig. 3.1). An algorithm has a starting point that will receive zero or more inputs (Fig. 3.1), a processing body being the finite and definite set of instructions that unambiguously specifies the steps for processing (the computation of) the given input. When executed it will produce the output by taking the input through the sequence of well-defined steps, as shown in the diagrams below (Fig. 3.1).

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39. Virtual is in contrast to physical and materialized, and can also mean possible in reference to solutions in the search domain (DeLanda 2013, 24). As Manuel DeLanda emphasises, “the virtual is not opposed to the real but to the actual. The virtual is fully real in so far as it is virtual. . . . Indeed, the virtual must be defined as strictly a part of the real object—as though the object had one part of itself in the virtual into which it is plunged as though into an objective dimension” (DeLanda 2013, 24).

40. This is a short description intended to convey the purpose of this research. For a thorough explanation of the concept of algorithm, see Andreas Blass and Yuri Gurevich, “Algorithms: A Quest for Absolute Definitions” in Bulletin of the European Association for Theoretical Computer Science, 81:195–225, 2003 (Blass and Gurevich 2003).
An algorithm is a human-made set of instructions that is finite in size, and working with algorithms involves formal logic and computation. The above example is a simple task; usually algorithms are employed for more complicated and complex tasks that go beyond a human’s capacity for processing information. For instance, while it is easy to add two small numbers using one’s fingers, when the number gets longer and the task more elaborate—e.g., adding two long numbers, then multiplying them with another number, dividing them with a new number, and so on—even a person who knows how to add and subtract small numbers using the fingers would employ an algorithm for defining the arithmetic procedure to solve the problem.

Algorithms are not new. The first nontrivial algorithm was Euclid’s algorithm for computing greatest common divisors (Knuth 1981, 318). The word algorithm as well as the idea of studying algorithms comes from the ninth-century Persian mathematician al-Khwārizmī, who “laid out the basic methods for adding, multiplying, and dividing numbers—even extracting square roots and calculating digits of π” (Dasgupta, Papadimitriou, and Vazirani 2006, 11). These procedures to aid humans in solving problems “were precise, unambiguous, mechanical, efficient, correct—in short, they were algorithms” (Dasgupta, Papadimitriou, and Vazirani 2006, 11). However, because there is no formal definition of algorithm, it remains a difficult concept to pin down. Hartley Rogers Jr. nevertheless informally defines several features of algorithm that are relevant for the purposes of this research:

*1. An algorithm is given as a set of instructions of finite size. [. . . ]

*2. There is a computing agent, usually human, which can react to the instructions and carry out the computations.

*3. There are facilities for making, storing, and retrieving steps in a computation.

*4. Let P be a set of instructions as in *1 and L be a computing agent as in *2. Then L reacts to P in such a way that, for any given input, the computation is carried out in a discrete stepwise fashion, without use of continuous methods or analogue devices.

*5. L reacts to P in such a way that a computation is carried forward deterministically, without resort to random methods or devices, e.g., dice. (Rogers 1967, 2)43

Rogers notes that “virtually all mathematicians would agree that features *1 to *5, although inexactly stated, are inherent in the idea of algorithm” (Rogers 1967, 2).
3.2. Various computing agents and the language of algorithm

An algorithm is a set of well-defined instructions that can be performed and which itself does not compute to perform tasks. The execution of an algorithm requires a computing agent, which “react[s] to the instructions and [carries] out the computations” (Rogers 1967, 2). It is together with the computing agent that an algorithm is capable of processing information.

The interdependency between the algorithm and the computing agent points towards the significance of the communication links between them. The steps and processing rules in the algorithm must be expressed with respect to the capacity of the computing agent. The computing agent that Rogers refers to is a human; in the example of the tea-making algorithm, for the algorithm to be executed by a human the instructions must be expressed in a language that can be understood and carried out by a human. Thus the kind of algorithm and the language in which it is expressed vary according to the kind of computing agent used to process the information.

3.2.1. Mechanical computing agents

There are mechanical computing agents that are fed algorithms to perform tasks. An example is the Jacquard loom, a predecessor to the modern computer designed by the French engineer Joseph Marie Jacquard in 1801 to perform the precise task of automated knitting. The loom could be “programmed” to create a large number of fabrics with variations in their patterns; the program—that is, the algorithm—consisted of punch cards whose hole patterns provided precise instructions to the loom to knit and weave yarn in a way that would result in a patterned fabric. Each punch card had multiple rows of holes, and each row corresponded to one row of the final fabric. By changing the punch cards or combining various punch cards—varying the hole patterns that were fed to the loom—textiles in various patterns could be made. Here, the instruction to knit a carpet is the algorithm.

41. An algorithm can be instructed to generate an algorithm, but the origin of the order is a human construct. An algorithm can be created by observing natural processes or phenomena (e.g., algorithms for representing the so-called fractal phenomena occurring in nature) or can be constructed based entirely on cognitive models (e.g., Karmarkar’s algorithm).

42. According to Knuth, “the Euclidean algorithm is the granddaddy of all algorithms, because it is the oldest nontrivial algorithm that has survived to the present day” (Knuth 1981, 318).

43. Worth considering alongside Rogers’s list are Vladimir Kolmogrov’s earlier intuitive ideas about algorithms:

“An algorithmic process splits into steps whose complexity is bound in advance, i.e., the bound is independent of the input and the current state of the computation.

Each step consists of a direct and immediate transformation of the current state.

This transformation applies only to the active part of the state and does not alter the remainder of the state.

The size of the active part is bound in advance.

The process runs until either the next step is impossible or a signal says the solution has been reached.” (Blass and Gurevich 2003, 9)
3.2.2. Electronic and digital computing agents

Today, the computer is a computing agent that can be fed with algorithms to perform tasks and carry out computation. When it comes to the computer, it is important to distinguish between algorithms made by architects and algorithms made by programmers. For a computer to perform it must be provided with a specific set of instructions that dictates its actions. These instructions are algorithms. However, the computer applies and executes algorithms at multiple levels. Usually when a designer describes an algorithm it is done in a computer program (e.g., scripting in CAD software), but every computer program is itself an algorithm. A program is a sequence of statements in some language—programming language or machine-level instructions. Vaidyeswaran Rajaraman describes a computer program as “an algorithm expressed using a precise system of notation which can be interpreted and executed by a computing machine”; this notation is called “programming language” (Rajaraman 1993, 3). Usually an algorithm created by a designer is on a different level, which avoids the low-level detail of exactly how things are implemented in the machine language: the algorithm provides instructions to the computer and computer programs—with some more intermediary steps—which then carry out the computation. In other words, there are machine-language algorithms that a computer program uses to make the hardware perform a task, and algorithms that are given to the computer and computer programs by designers, which are sets of instructions for the computer to perform and generate outputs.

For architectural design, “the application and execution of algorithm in a computer happens through programming languages, which enables computing procedures” (Menges and Ahlquist 2011, 11). The recent application and execution of algorithms in architectural design has been enabled by the scripting languages and scripting environments available in 3D computer graphics and CAD software. Examples of such scripting languages are 3D Max Script, Maya Embedded Language (MEL), Visual Basic and Python in Rhino, Processing (Java), and GC script in Generative Components. These scripting languages can be used to customize 3D modelling or CAD software. CAD and 3D modelling programs themselves employ algorithms to process data and perform tasks—algorithms with low-level detail of how things are implemented in the machine language.

3.2.3. Material computing agents

A machine is not necessary for computation. There are other forms of computation that do not depend on machines. Another agent for algorithms can be material, which is capable of computation as well as facilitating making, storing, and retrieving steps in a computation. For instance, soap film is a material capable of computing its minimized total surface area subject to its boundary. A soap film can be created by dipping a wire frame into a soap solution, with the shape of the wire and other conditions producing the form of the film on the wire. For every boundary, the material is in motion until it finds its equilibrium state—a state of physical balance where the inner quality of the material and the natural forces of the environment are equalized.

In origami, a set of geometric instructions of a finite size can be made and stored in the paper in such a way that when the forces (inputs) are applied the paper will react to the instructions and carry out the computations. Here the paper can adapt and react to the logic of geometric instruction in a closed boundary (the algorithm). Here there is mutual informativeness within and between the material, its environment, as well as its algorithm. The making of the hyperbolic paraboloid origami in Experiment 3 is, in part, exploring this topic (Fig. 3.2).
This includes programs that do not perform numeric calculations.

To discuss the many intermediary steps involved would fall outside of the purpose of this research.

Note the difference between programming and scripting: scripting languages are interpreted languages and use libraries of functions that enable easy coding. The codification of a design intention using the scripting languages available in 3D software saves the designer from direct programming. Unlike programming, scripting doesn’t require the designer to go through an explicit compiling step; it allows the designer to connect predefined building blocks and libraries that perform complex geometric operations. Programming is a language that is used to control the mechanical parts of machines directly. It is a machine language, whereas scripting controls software.

A surface that has the least possible area for that fixed boundary is known as minimal surface.

It is possible that this is very similar to the concept of the Turing Machine.
Some may disagree with the idea that a set of geometric descriptions can be considered an algorithm, and the material considered its computing agent—but if the language in which the algorithm is expressed can change from symbolic and diagrammatic language processed by a human as a computing agent, to a pattern on a punch card to be computed by a loom, to scripting in CAD software to be computed by a computer, then can it not be changed from scripting to geometry to be computed by a material? In “Algorithms: A Quest for Absolute Definitions,” Andreas Blass and Yuri Gurevich ask “what kind of computations can be carried out in our physical universe? [. . .] The question concerns what algorithms are physically executable. We don’t expect a definitive answer soon, if ever” (Blass and Gurevich 2003, 13). Reading their question from the point of view of a designer, it opens up the possibility of a shift in the computing agent as well as in the format of the algorithm.\footnote{49}

The term \textit{material computation} being used here needs some clarification. The term has been widely used in the computational field of architecture, and has been discussed in various disciplines. The author believes that the nature of the computation that is carried out by machine (e.g., computer, loom) is surely different from that carried out by material’s morphogenesis (e.g., the morphogenesis of paper, soap bubbles, or fabric). The manner in which processes in material occur differs fundamentally from the way they are carried out using a machine. Machine execution of an algorithm is different from when an algorithm is executed by material. While the act of computing by computer deals with processing digital information composed of 0s and 1s, changes in material are continual and not numeric.\footnote{50} The claim here is not that the soap film or origami paper actually perform computation through morphogenesis; rather, they serve as our investigation of the morphogenesis of material in terms of information processing. In other words, one can view and discuss processes occurring in material as information processing. For instance, in the second part of Grzegorz Rozenberg, Thomas Bäck, and Joost N. Kok’s \textit{Handbook of Natural Computing}, which presents a number of computing paradigms at the intersection of computer science and natural science, the authors investigate the computation taking place in nature—such as the computational nature of self-assembly and the computational nature of brain processes—in terms of computation.\footnote{51}

In summation, algorithms themselves are no more than sets of instructions, and do not compute; execution of algorithms and computation require a computing agent. Computation as an act of processing information is different when carried out by a human, a machine, or material. As such, the design of algorithms is tightly connected to the nature of their computing agents, as they must communicate with each other: the steps and processing rules in the algorithm must be expressed with respect with the capacity of the computing agent. This also means that \textit{what one can explore with algorithms as a design medium will be constrained by the capacity of the computing agent in use.}

\subsection*{3.3. Application of algorithms in CAD}

As mentioned in the previous chapter, the application of algorithm as a design medium in architecture has been made possible by the scripting languages and environments available in 3D computer graphics and CAD software, which have enabled designers to go beyond the limitations of mouse-based modelling (which had constrained the designer to factory-set ways of 3D modelling). The introduction of graphical algorithm editors such as Grasshopper, which runs within Rhinoceros 3D CAD software, has made algorithm as a design medium accessible to designers who do not have knowledge of programming or scripting. This interface allows the designer to build the descriptive definition of a geometric construct us-
ing the Grasshopper definition, with which the user can easily move around the descriptive definition of the geometric construct. To create a 3D model, the designer describes what the computer should do in precise steps, expressing the steps in terms of algorithm within the algorithmic interface (scripting environment or graphical algorithm editor). Once executed, the computer computes and generates the outputs. The computer is used to process information through procedures that are expressed as an algorithm.

By using this kind of interface, the designer can deal with greater complexity in the design. The designer is not designing the end product, but defining the associative relation between the geometric elements, and the influential factors involved in a design framework in terms of generic algorithms. Therefore, many parameters could be linked into the design exploration model. A number of architectural projects have been built in which algorithms were used as a medium for design, and computation was used as a method. 52

Algorithmic thinking is used to describe a way of thinking and working in design. While the initial parametric-associative technique offered by software such as Generative Components (GC) was based on algorithms, the creation of 3D computer models through its interface was not necessarily the act of designing algorithms. As presented in the previous chapter, the symbolic graph offered by GC was a representation that let the designer observe the parent-child relations, but designers could not use the graph as a tool to construct geometry (see Fig. 2.4 in Chapter 2).

What in this dissertation is referred to as algorithmic technology that enables computation—processing of information—as part of design process is built upon the parametric and associative modelling system described in Chapter 2. It has the further advantage of enabling the designer to freely design and modify the algorithm—the logic and definition of the geometric construct. Here, the designer performs algorithmic thinking and the act of designing algorithms.

3.4. The nature of algorithms in relation to the nature of design processes

The synergy of algorithm and computer (or the application of algorithm in 3D modelling programs) brings generativity and a certain degree of automation to the design process. Generativity is the ability to generate, produce, create, and reproduce outputs in the form of numbers, text, images, 2D or 3D geometry, and other forms. In mathematics, the word generative is used to describe the ability to form a line, surface, or solid by notionally moving a point, line, or surface respectively. A generative approach produces outputs through the application of a finite set of rules to a given input. When a line moves, it generates a sur-

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49. This is the author’s own reading of their question. At the core of Blass and Gurevich’s discussion around this question are numbers, quanta, and programming language. The first part of their paper is a brief review of the separate histories of Church’s and Turing’s theses, followed by a brief overview of the path from Turing’s original analysis of what we might call a classical algorithmic procedure to its generalization in the work of Kolmogorov and Uspenskii, as well as Schönhage.

50. Even though Rogers, in his description of algorithm, emphasises that “the computation is carried out in a discrete stepwise fashion, without use of continuous methods or analogue devices,” (Rogers 1967, 2) in this dissertation the author has expanded the domain of computing agents to material.

51. In the context of this dissertation the terms material computation and material computing are reserved for when data are encoded into material to perform computation—in the manner of Skylar Tibbits’s designed and printed 2D, 3D, and 4D self-assembling objects, or even origami.

face. To produce a surface, the line as an input goes through a step-by-step procedure. With each variation in the way the line is moved in space, a new surface is generated. In relation to the design field, Hartmut Bohnacker, Benedikt Gross, Julia Laub, and Claudius Lazzeroni use the term *generative design* to describe “a revolutionary new method of creating artwork, models, and animations from sets of rules, or algorithms” (Bohnacker et al. 2012, cover). In this research, the term generative is used to refer to the application of algorithm affiliated with the computer as a design medium, and emphasises the character of a design process in which outputs are automatically generated. The employment of algorithm as a design medium introduces the generative approach to design, with outputs produced and reproduced if the same step is executed. Algorithm in this context is a productive tool with outputs.

The use of algorithm brings a certain degree of automation to the design process. *Automation* denotes the autonomous part of a process that works by itself with little or no direct human control; in terms of the design process, *automation* refers to the phase of the design process that proceeds spontaneously without the conscious control of the designer. Once the designer defines the steps and rules of an algorithm, its execution will automatically produce the outputs; while the designer describes the rules of an algorithm, the interpretation of these rules and their translation into outputs is done by digital computation performed by the computer. This inherent character of algorithms causes gaps between the direct input of the designer and the outputs of the algorithms—the designer does not design outputs, but rather the rules and processes that the program automatically executes to produce the outputs. The designer is not concerned with how to draw a curve, for instance, but rather with how to describe a curve which will be computed automatically.

Every tool enables and constrains the way one designs with it. Using algorithms limits the designer in the articulation of geometry, but allows the designer to explore a broad spectrum of possible forms. As Mario Carpo has pointed out, a notational system, a certain way of drawing, is precise but has certain limitations: for instance, when using projective tools, the designer can explicitly articulate the drawn curve but cannot draw every potential curve (Carpo 2011, 18–23). Using algorithm as a design tool enables *all of the potential curves* to be generated: “given a mathematical function, computers could visualize an almost infinite family of curves that share the same algorithm, of which the parameters can be changed at will” (Carpo 2011, 90).

While generative tools such as algorithms are expressed using a notational system, the algorithm itself is not a notational system: it is a ruleset. Designing with conventional notational systems is more about the representation of a design intent, while designing by means of algorithm is more about the exploration of alternative design possibilities. Prior to digital tools, designers such as Antoni Gaudí, whom Carpo refers to (Carpo 2011, 32), and Frei Otto chose to invent their own tools to aid them in the process of designing things that could not easily be worked out with projective tools.

Algorithm as a means for the conceptualisation of ideas and generating outputs relies on the designer formalising an idea by a clear set of rules to be computed—that is, the nature of the algorithm challenges the designer to abstract an idea in a clear and consequential way. In architectural design, ideas are not always clear in the early design stage and are developed through an iterative design process as result of evaluations of the outputs of the design process and the refinement of the design. Following this method, one question is how to formulate vague ideas clearly in terms of algorithms; another concerns the satisfactory result of the algorithm’s outputs—does an algorithm immediately and automatically produce satisfactory results for the design quest?
The answer to the second question is simple: algorithms do not produce satisfactory results automatically—the outputs must be improved through the conscious observation and critical evaluation of the designer. The designer must then modify the underlying logic, rules, and parameters of the initial algorithm in order to produce new sets of outputs. Eventually, after a number of iterations of the reformation of the algorithm and observation and evaluation of its outputs by the designer, the algorithm is interpolated and refined and the design is developed (Fig. 3.3). This requires interaction between the designer and the outputs of algorithms in such a way that the designer makes significant observations, evaluates outputs, and consequently develops and interpolates the algorithms based on the design context.

Figure 3.3. The diagram illustrates how the algorithm and the design idea—having emerged from material exploration or the designer’s mind—is reformed by the designer’s evaluation of the algorithm’s outputs after every iteration.

Figure 3.4. In order to shift the designer’s evaluation mode from a solely intellectual one to the tangible and material one in the diagram, the immediate outputs of the algorithm must be materialised.

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53. It is not clear who coined the term generative design. However, the term generative art was used to refer to computer- and process-based art as early as 1965, in the context of the Georg Nees exhibition Generative Computergraphik. See Margaret A. Boden and Ernest A. Edmonds, “What Is Generative Art?” in Digital Creativity, Volume 20, Issue 1–2 (2009), 21–46. The term “generative mathematics” was also used by Herbert W. Frank in a study of mathematical operations that enable the generation of images in art; see “Mathematics as an Artistic-Generative Principle,” in Leonardo, Supplemental Issue, Volume 2 (1989), 25–26.

54. The designer is a sentient being. While our current machines do not have consciousness, that does not mean that future machines will not become conscious.
The nature of the outputs affects the way the designer interacts with them, and consequently how the designer develops the algorithms towards the final product. “Unlike physical tools where unpredictability is of a mechanical or chemical nature, algorithmic tools are abstract, rational, and intellectual in nature and therefore related to the human mind. So, in that context, the output of an algorithm must be associated to a human mind, either the programmer or the designer. Anything else would be absurd because it would involve an intellectual process without the presence of a human mind” (Terzidis 2006, 23).

The immediate outputs of algorithms are intellectual ones, such as numbers, text, geometry, and so on. In the context of architecture as material practice, it is crucial to explore, examine, and evaluate algorithmic outputs beyond the numerical and geometrical. Matter and material things, as well as tangible explorations of design, are important to proceeding with and developing the process. Material, tactile, and physical properties enable the designer to drive the exploration beyond the numerical. Proceeding based on the pure, immediate outputs of algorithms would limit the design to purely intellectual evaluation. For the designer to enter into a tangible exploration when using algorithm these outputs must be materialised (Fig. 3.4). The significance of material and physical model making for design exploration is discussed in the next chapter.

The first question, regarding how the designer can abstract vague ideas in such a way that they become formalised clearly in terms of algorithm, contains something of a contradiction. In general, the use of algorithm as a tool to conceptualise ideas requires some degree of formalisation prior to the act of designing the algorithm: the designer must plan and formalise the design idea ahead of time and turn it into an “understood model”—regardless of whether the idea originates in physical modelling or comes directly from the designer’s mind. For instance, the designer must define which major elements should be dependent upon other elements and define the parameters of the model and the hierarchy of dependences between the parametric geometries and functions—which is to say, the designer must use the parametric-associative technique. Rick Smith, a CATIA expert, has criticised parametric modelling for its rigidity and for the unpleasant consequences of preformula-

Smith was employed by Gehry Partners to assist in realising geometrically complex structures such as the 1991 Barcelona fish sculpture.

He writes that “when you model using parameters you are programming following similar logic and procedural steps as you would in a software programming. You first have to conceptualize what it is you’re going to model in advance and its logic. You then program, debug and test all the possible ramifications where the parametric program might fail” (Smith 2007, 2). In doing so designers “may over constrain or find that [they] need to adjust the program or begin programming all over again because [they] have taken the wrong approach” (Smith 2007, 2). Thus once the algorithm is introduced to a stage of design, that stage is systemised.

The pre-formalisation and foresight is almost a necessity. The move from a vague idea to determining the idea as an understood model starts with early conceptualisation, where other design instruments, such as sketches, diagrams, and physical models may be helpful aids in the preformalisation, preconceptualisation, and communication of ideas. For instance, material exploration through physical modelling at the early design stage can inform how the designer conceptualises an idea, and can shift the exploration beyond the immediate constraints of the algorithmic rationale. Also, sometimes the designer does not begin with an idea, instead an idea emerges out of the early physical modelling exploration.

It is possible to choose the material for manual modelling in direct relation to aspects of the materialisation stage—its constraints and potentials—in order to ensure the constructability of the full-scale counterparts. The designer can create the physical models in such a way that they can work in unison with the algorithm to enable a hybrid digital and physical design exploration (Fig. 3.5). In Experiments 2, 3, and 4, various interdependent relations between manual physical and digital-computational modelling processes are examined.

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56. Smith was employed by Gehry Partners to assist in realising geometrically complex structures such as the 1991 Barcelona fish sculpture.
While algorithm is very powerful for enabling the computation of complex processes and generating many outputs, it is still the designer who, through active choice, conceptualises the design idea by selecting certain design mediums and giving them particular roles and agency. To seek or conceptualise an idea the designer relies on skills in both the numerical and material domains. When working with algorithm, the exploration is limited to being a numerical and logical one, while working with material shifts the exploration to the empirical and tactile. Both domains of exploration have their particular inherent properties and capacities that constrain and enable design exploration.

When designing, the designer doesn’t always have a defined concept; often the designer finds inspiration in already existing things, such as nature or the modelling material. Materials have properties and capacities that in some way guide the designer in the exploration, and the exploration itself can be a source of inspiration and the generation of design ideas as well. The question is, can algorithm also be a source of inspiration and idea generation? In fact, algorithms have often been used as source of inspiration from which design ideas emerge, or as a tool that has given the designer access to another domain of knowledge—for instance by allowing the designer to explore a mathematical formula—and apply it in the context of the architecture. The next section discusses this further.

3.5. Algorithm for architecture as material practice

The pure employment of algorithm without consideration of the material world can be seen to provide an interface for the designer to access and visually generate potential forms and patterns, which manifest around generative procedures through scripted logic. Algorithm’s employment in architecture as material practice involves the conscious redefining of rules and codes that are meant for digital manufacturing methods and create consistency and precision between a logical-formal exploration and the processes of materialization.

The recent application of algorithms in architectural design has been diverse, and it is not the objective of this section to point out all of the different applications of algorithms in architecture. This research identifies three approaches to using algorithms in the design process in the context of architecture as material practice:

- implementing existing algorithms for a design idea, intent, or problem (problem solving approach);
- exploring and investigating the architectural potential of existing algorithms based on visual exploration (explorative);
- designing and creating a set of algorithms for a design idea, intent, or problem (design approach).

3.5.1. Implementing existing algorithms for a design problem

One can employ an existing algorithm for an existing design problem or design intention (solve a design problem). In this approach, a pre-developed algorithm becomes employable when we find an application for it in the design problem at hand. In this case there is a clear design intention or problem, for which a particular algorithm becomes the means or solution. An example is the employment of algorithms that generate developable surfaces in the attempt to parametrically model a twisted, bent, or folded strip of paper. In the case of Experiment 2, Strip, in this dissertation, there was a clear intention to mimic the behaviour
of the paper strip; the developable surface was found to be a suitable model to represent a strip of paper geometrically, parametrically, and digitally.58

There are various algorithms for solving design problems, and choosing the right one is crucial. As Dennis Sheldon has said, “once you want to get things into a digital world you have to pick a set of algorithms, you have to pick a digital language. The selection of each algorithm leads to completely different representations, completely different means of building, and completely different economics, and completely different resulting form” (2014b). For example, there are many already developed algorithms that can be employed to generate developable surfaces in CAD, such as algorithms that generate developable Bézier surfaces through a Bézier curve of arbitrary degree (see Bo and Wang 2007), linear approximation algorithms for developable NURBS surfaces with an emphasis on controlling the curve of regression (see Pottmann and Wallner 1999), and algorithms for developable surfaces from arbiter 3D polyline boundaries (see Rose et al. 2007).59 These algorithms lead to completely different outputs, and each gives the designer access to different control parameters. In Experiment 2, Strip, for instance, the author and design team searched for algorithms that could enable the generation of a developable NURBS surface from a single 3D spatial curve (Fig. 3.6). This search was due to the particular design intentions and problems at hand for this task, and the choice of algorithm was crucial in enabling a degree of intuitive exploration as the design exploration moved from a physical environment to a digital one, as well as in the economical materialisation of the design idea in the latter phase of the process. A developable surface algorithm that required two curves as an

Figure 3.6. Generating a developable surface from a single 3d spatial curve to represent the overall form assumed by paper strip (a), splitting the strip and assigning thickness base on constraints of fabrication tools an material (b).

57. In their book Algorithm Design, Jon Kleinberg and Éva Tardos approach algorithms by looking at the real-world problems that motivate them and develop the basic techniques of algorithm design by drawing on problems from across many areas of computer science and related fields. They mention that “the algorithmic enterprise consists of two fundamental components: the task of getting to the mathematically clean core of a problem, and then the task of identifying the appropriate algorithm design techniques, based on the structure of the problem” (Kleinberg and Tardos 2006, xiii). It can seem as though the use of algorithms is restricted to finding solutions to problems: the algorithm responds to a particular problem. For Kleinberg and Tardos, it is obvious what the problem they have encountered is, what they already know about that problem, and how to proceed to solve the problem through the design of algorithms. In architectural design, however, the problems are not always clearly defined and in many cases are developed throughout the design process. As the design expands in complexity, so do the problem and the solutions to the problem. Moreover, problem solving is not the ultimate goal of architectural design. So a question can be raised as to what the scope of algorithm in fields like architectural design is.

58. Developable surfaces are those surfaces that can be unfolded into a plane with no distortion. They are a good representation for sheet materials such as strips of paper, wood, or metal.

59. See also the section on differential forms and application to surface constructability in Dennis Shelden’s dissertation (Shelden 2002, 157–202).
input would lead to a different continuation of the design exploration in the
digital environment than one that required one curve. In this experiment,
the author found that selecting a suitable algorithm to the design problem
at hand was necessary.

In Experiment 2, the challenge was to choose algorithms that would al-
low the representation of the overall form suggested by the paper strip—a
small-scale physical model—digitally and parametrically, while also allowing
the designers to interpolate the algorithm further to ensure the con-
structability of the form from sheet material as a 1:1-scale prototype within
the dimensional limits imposed by the cutting bed of the digital fabrication
machine. In this case, the algorithm had to generalize the paper strip while
simultaneously specifying a way of regenerating it digitally based on the
constructability requirements (Fig. 3.6). This use of algorithm for solving a
specific design problem is a search for its potential to represent the design
problem or question in hand parametrically, digitally, and generatively. It
requires the designer to find correlations between the design problem and
the existing algorithmic models, and the knowledge required extends into
disciplines beyond conventional design practice.

The concern with this way of employing algorithms in design is that the
algorithm employed to address the design problem was not initially de-
signed for the specific problem at hand, but for an entirely different prob-
lem. Consequently, when a designer uses an existing algorithm to design,
they may not be aware of the particular mechanisms and specifications of
the chosen algorithm, which can impact the design problem. Furthermore,
there may be issues concerning the design problem that were not antici-
pated by the original author of the algorithm. Consequently, this method
of employing algorithm will eventually require the designer to enter the
sphere of algorithms to redefine, modify, interpolate, and redesign it in a
way that will suit the problem at hand. In most cases, there is no inspector
or expert who can check whether or not the designer is implementing a
suitable algorithm for the design problem at hand.

3.5.2. Exploring the architectural potentials of existing algorithms

Exploring the architectural potentials of existing algorithms stems from
visual inspiration. This approach uses the algorithm as a source of inspi-
ration and as a driver to develop design concepts: the designer turns well-
known algorithms that were developed by other disciplines to describe
nature or natural phenomena into models that drive architectural design.
This is not necessarily the use of algorithm for a particular design problem,
but rather a search for what potential it may have for architecture—the de-
signer attempts to understand a particular algorithm’s performance with-
out necessarily having an immediate idea of what it could be used for. This
understanding usually arises from visual exploration—some algorithms,
when executed, generate outputs that are visually interesting and encour-
age the designer to implement them—leading to the exploration of their
performance by the designer once the parameters are changed.
In recent years, a number of visually interesting algorithms have encouraged designers to implement them in design processes. Fractal algorithms, which generalize the natural phenomenon known as fractals—patterns in nature that are repeated and recur progressively at every scale—are one example. Another example is Fortune’s sweepline algorithm, one of many algorithms for generating Voronoi diagrams and patterns. Voronoi patterns occur in nature, for example in the spots on a giraffe’s body.

These algorithms are usually abstractions of discovered natural phenomena, rather than having been created by the human mind alone: as Terzidis points out, “contrary to common belief, algorithms are not always based on a solution strategy conceived entirely in the mind of a human programmer. Many algorithms are simulations of the way natural processes work and as such they must not be regarded as human inventions but rather as human discoveries. Unlike inventions, discoveries are not conceived, owned, or controlled by the human mind, yet as abstract processes they can be captured, codified and executed by a computer system” (Terzidis 2006, 19).

It is not easy to anticipate the potential that these algorithms have for architecture until they are explored through architectural means of communication and for architectural values. For example, Benjamin Aranda and Chris Lasch have used algorithms that describe natural phenomena to arrive at results that are artificial and manmade. In their Recursive Sketch experiment (Fig. 3.7), for example, they use the “cracking algorithm,” which “produces a construction in which each edge is shared by exactly two shapes and each edge is continued” to design a building (Aranda and Lasch 2005, 56).

Aranda and Lasch’s approach is to begin by writing recipes that describe the logic behind the phenomenon, which consequently generates a pattern, in order to explore what this algorithm and its generated pattern can mean for architecture. They use conventional architectural means of commu-
munication, such as drawing, digital modelling, and physical modelling, all of which link to visual and tactile communication, and they shift the exploration from pattern to volume by moving from two-dimensional drawing to colouring and shading. First they bring algorithms into the design by visualizing them as patterns. Then, by integrating material knowledge, they transform pattern to volume, which gives rise to physical models. This is when the knowledge of making and material practice plays a critical role in creating an artificial product.

Aranda and Lasch’s work is an example of the architectural mode of employing algorithm, which takes something generic like the “cracking algorithm” and makes it architectural by means of visualization and materialization. The process of translation from generic algorithm to visualized pattern to physical model entails expert knowledge in design and making. Though initially inspired by the complexity of nature, the designer does not have to wait for nature to decide how it should be artificially made: design is not just a means of reproduction, and the designer has the freedom to choose, make decisions, and create with the support of and with respect to project frameworks and constraints.

3.5.3. Designing algorithms for design intentions

Not all algorithms that are useful for design already exist, and the designer may have to develop an algorithm based on a project framework. To do so, the designer has to (1) understand the project framework, (2) formulate the design idea, and then (3) formalise it clearly in terms of algorithm. The design intention is broken into smaller problems (decomposed) and then worked out to an understood model; the designer can then enter into the process of composing an algorithm in order to address the design intention in a finite number of steps. In the formulation of design by means of algorithm, the designer describes a sequence of instructions, which in turn points towards possible solutions for a partially known problem.

Composing an algorithm is a design process in itself, which relies on the designer's ability to think and design in terms of algorithm. The terms algorithmic thinking and computational thinking have been widely used to describe this ability. Brady Peters defines algorithmic thinking as “taking on an interpretive role to understand the results of the generating code, knowing how to modify the code to explore new options, and speculating on further design potentials” (Peters 2013, 10). Jan Cuny notes that computational thinking can be understood as “the thought processes involved in formulating problems and their solutions so that the solutions are represented in a form that can be effectively carried out by an information-processing agent” (Cuny, Snyder, and Wing 2010, 10). For the author, algorithmic thinking is a particular way of thinking about and working in design that, at its core, involves the ability to think more logically about design, whereas computational thinking is the ability to solve problems by going into mathematical equations (such as getting into the Grasshopper component, which is normally expressed as a black box).

In the context of architecture as material practice, the designer should be able to break down the complexity of the material capacity, fabrication logic, and construction methods, and work out a qualitative schema for these empirical problems which is then described in terms of descriptive algorithm by means of a particular system of instructions, such as scripting or the node-based system offered by Grasshopper. An example is designing an algorithm that allows the designer to first design a freeform roof which is to be built from planar parts, and then to explore alternative solutions. A common approach is to design an algorithm that generates a digital freeform surface, and then expand the algorithm to
These are step-by-step instructions that are interpretable and computable by the computer program (in the context of this research, CAD) and the computer.

On algorithmic thinking, see Gerald Futschek’s paper “Algorithmic Thinking: The Key for Understanding Computer Science,” in Evolution and Perspectives: The Bridge between Using and Understanding Computers, proceedings of the 2006 International Conference on Informatics in Secondary Schools (Berlin and Heidelberg: Springer-Verlag, 2006), 159–168. According to Futschek, “algorithmic thinking is somehow a pool of abilities that are connected to constructing and understanding algorithms:
- the ability to analyze given problems
- the ability to specify a problem precisely
- the ability to find the basic actions that are adequate to the given problem
- the ability to construct a correct algorithm to a given problem using the basic actions
- the ability to think about all possible special and normal cases of a problem
- the ability to improve the efficiency of an algorithm.” (Futschek 2006, 160)

This could mean developing an algorithm to explore some scenarios of the materialization stage in the early design process, developing an algorithm to bring a physical model into the digital domain parametrically, or just describing the geometric association of a form algorithmically.

Figure 3.8. Using algorithms and associative-parametric techniques, designers can explore alternative forms of doubly curved freeform surfaces that can be built from planar components. The two examples show two different techniques of surface rationalization: triangulation and eggcrate. The models were produced by students Jonas Haraldsson and Susanne Segerstein.
design throughout the design process—algorithm influences the designer’s intention and the design itself.

This section will examine in detail the use of algorithm for exploring geometric form with respect to its materialisation, and for creating an intricate network of models that work together in a productive manner to enable significant innovation and findings. What does the use of algorithm in the exploration and design of geometric form with respect to materialisation entail? How do algorithms provide links between models? Do they act as translators between different information formats, driving one entity with the outcome of another? And how do new things emerge by creating such links between different entities? These questions are explored with respect to the capacity of the algorithmic tools available in CAD programs.

3.6.1. Exploring geometric form

The application of algorithm to define and create the geometric form of a structure entails a systematic arrangement of code. By means of code or an algorithmic interface such as Grasshopper, a formal idea is translated into a set of rules described in terms of an algorithm. These rules or principles describe formal arrangements that, when executed, will result in a number of potential geometric forms (Fig. 3.9): “Instead of modelling an external form, the designer articulates an internal generative logic, which then produces, in an automated fashion a range of possibilities from which the designer can choose an appropriate formal position for further development” (Kolarevic 2003a, 13). In other words, the designer does not draw geometric objects to create a form, but rather describes the geometric objects and their associated relationships in terms of values and parameters—describing, for instance, a circle to be created from a point and radius or from three points on its perimeter; to continue the same example, by assigning different values to the radius and environment parameters, variant circles can be produced.

Such an approach can produce not only one form, but a complete spectrum of related forms when certain parameters are changed (Fig. 3.9). The focus shifts from notationally drawing a form to “developing processes, in the form of algorithms or generative rules, from which a specific result is then brought about through the definition and emphasis on influencing values and parameters” (Menges 2010, 3). The designer explores alternative forms by varying defined parameters.

As mentioned in the previous chapter, the application of algorithm in architecture is accomplished via CAD and commercial 3D modelling software through scripting, programming, or algorithmic interfaces that are equipped with associative and parametric system. The parametric-associative system used in CAD-geometric models employs a particular sequential and hierarchical composition of geometries, as well as a particular way of propagating changes through the structure of the geometric dependency. The current parametric-associative dependency tree allows a one-way parametric relationship between parent and child geometry: that is, it allows propagation of effects only from the parents towards the children. Whereas child geometry is updated when the parent is modified, changes in the child do not affect the parent (Fig. 3.10).

The use of algorithm to define the logic of form and compute geometric forms involves defining and describing the particular way in which parts and whole exist and relate to each other to generate complex forms—forms which are visualized and represented by the associative arrangement and parametric articulation of geometry in terms of descriptive al-
The need to describe the computing logic prior to the act of exploring possible outputs is not an issue in the case of exploring the architectural potentials of existing algorithms, such as Voronoi generators. Therefore the way in which the designer describes the geometry and its geometric relationships is crucial, as that description will impact the spectrum of probable outputs. What is most important to understand is that the logic of a form has to be described prior to computing and exploring the possible outputs. In other words, in contrast to form exploration via material manipulation by hand, where the exploration is intuitive and integral to the act of manipulation, the creation of forms using algorithm requires the designer to describe the computing logic prior to the act of exploring possible outputs.67

Exploring geometric form cannot be done without attending to the relationships between the part and the whole, or the components and the overall structure. According to Christopher Alexander in Notes on the Syn-

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67. The need to describe the computing logic prior to the act of exploring possible outputs is not an issue in the case of exploring the architectural potentials of existing algorithms, such as Voronoi generators.
thesis of Form, “every aspect of a form, whether piecelike or patternlike, can be understood as a structure of components. Every object is a hierarchy of components, the larger ones specifying the pattern of distribution of the smaller ones, the small ones themselves, though at first sight more clearly piecelike, in fact again patterns specifying the arrangement and distribution of still smaller components” (Alexander 1964, 130). The design methodology that is offered by algorithm allows designers to access and alter every level of component, “piecelike” or “patternlike,” at any time throughout the design process.

When working on a formal level, part-whole relationships cannot be ignored; architectural elements are the unique details and component parts that, together, form the structure as a whole. Algorithm as a design medium enables the designer to deal with a complex hierarchy of components, leading to “wholes that are not reducible to their parts” (Reiser and Umemoto 2006, 50). According to Jesse Reiser and Nanako Umemoto, such a structure emerges out of a “hierarchy that is not simply nested in scale and distinct from the orders that lie above and below it” but from “organizational principles that promote communication across the scales, in which the particular is able to affect the general and vice versa . . . this requires methodology that involves both top-down and bottom-up logics operating in a feedback loop” (Reiser and Umemoto 2006, 50–51; Fig. 3.11).

Even though it is algorithms that enable such complex hierarchies, it is important to remember that the act of designing through algorithms still requires the designer to define the hierarchical relationships that lead to the sequential appearances of parts in the formal system. Thus, working with algorithms and using a computational approach does not mean rejecting the hierarchical concept of whole and parts, but introduces a new dimension by enabling access to different levels in the hierarchy as well as enabling the propagation of local changes on a global level and vice versa. However, a limitation of the parametric-associative geometric system is that the propagation of the changes is one-directional, always from parent to child: the parent is the driver and the child is the driven.

In creating form by means of the parametric-associative system, sometimes the whole is broken down into parts, and sometimes the parts come together to create a whole. In the first scenario changes in the whole are propagated to the parts, and in the second it is the reverse. Either a selected geometric concept—e.g., surface—represents the overall form of a structure, which should then have the capacity to transform into discrete units that can be fabricated as individual elements of an actual structure, or the selected geometric concept represents the individual elements of an actual structure, which then should smoothly merge into a coherent whole to represent its overall form.

Each of the experiments conducted examines the role of algorithm in enabling designers to define the parts-to-whole relationships of the form with reference to materialisation. These two ways can be demonstrated by looking at three of the experiments (Fig. 3.12).
In their *Atlas of Novel Tectonics*, Reiser and Umemoto speak of the “emergence of the new organizations and new architectural effects out of wholes that are not reducible to their parts” (Reiser and Umemoto, 50).

**Figure 3.12.** The diagram illustrates how the direction of the propagation of changes in each experiment: from the global representation of form to the local representation of form, the reverse, or both at the same time. Experiment 1, *Honeycomb*, exercises the propagation of the global changes to the local level. Experiment 2, *Strip*, exercises the propagation of the global changes to the local level. Experiment 3, *Hypar*, exercises the propagation of the local changes to the global level. Experiment 4, *Hyperboloid of one-sheet*, exercises the propagation of the local changes to the global level and global to the local simultaneously.

**3.6.2. Encoding aspects of materialisation into the geometric formation**

In the context of architecture as a material practice, the designer will want, at some point, to get the digital model out of the computer and into the physical world (materialize it).

One approach to design is to keep designing form regardless of what it will be built from, then post-rationalise it for fabrication and the desired construction material. Another is to consider aspects of materialisation (e.g., fabrication capacity and material constraints and potentials) at an early design stage and make them inherent to the exploration model and a driver of the formation process, iteratively exploring consequent design alternatives and the implications of materiality in those alternatives, informing the descriptive domain of design with empirical aspects of the materialisation stage. It is the second approach that is central to this dissertation.

Using algorithm and computation allows the designer to conceptually incorporate the underlying principles of digital fabrication techniques, material capabilities, structural behaviour, and assembly into the exploration domain. In encoding these underlying principles by means of algorithm, the designer abstracts and translates them into a logic executable by the computer. Encoding as a concept requires the designer to abstract particular empirical aspects or processes and translate them into an algorithm that can be employed at different moments throughout the design process. The source of information may be a particular parameter such as material thickness or the tool rotation angle, a part of the design process such as the conversion of a digital surface into discrete parts that can be fabricated, or certain aspects of fabrication, assembly, or construction. Most of the encoding occurs through defining the parameters to values derived from influential factors (e.g., values for the geometric twisting and bending of the developable surface).

To make materialisation integral to the computer-aided formation process, design intentions and underlying empirical principles are captured and encoded by means of algorithm. That is, they are translated into parameters in the logical description of form—the algorithmic definition of form. Here, there is a basic tension between the descriptive aspects of computational geometric formation and the empirical materialisation process. If the sector of activity in which geometric formation takes place is *descriptive* and the materialisation sector is *empirical* then the question is, how do we incorporate the empirical realm of material into the descriptive computational process? Cooperation between the two requires translation and abstraction. Capturing and encoding design intentions by means of algorithm involves the development of a qualitative schema (informed by the later empirical situation) followed by digital algorithmic definition—encoding the schema.
in terms of parametric-associative geometries using descriptive and algorithmic procedures—that can be later used by the designers to control and manipulate complex geometry (Fig. 3.13).

Encoding was exercised in the experiments in several ways. In Experiment 1, *Honeycomb*, various surface conversion techniques associated with CNC fabrication tools, including tessellating, contouring, and sectioning (“egg-crating”), were encoded algorithmically. The geometry of construction materials and their constraints (such as material thickness, maximum and minimum angles of joints, and maximum area of a component) were encoded algorithmically. This was done by defining parametric computational components and by setting a domain of values for their dimensions. Economic constraints were encoded algorithmically by assigning cost values to the area of all components.

Experiment 2, *Strip*, incorporated particular material capabilities (what a material could do). For example, the capacity of the material with respect to bending and twisting was encoded algorithmically by setting a domain of values for the geometric twisting and bending of the developable surface. As design continued and the material for the physical model changed, encoding enabled the designers to work with new constraints that emerged throughout the process.

In Experiment 3, *Hypar*, the process of folding paper and the limitations of the construction material—both planar materials—were encoded algorithmically by defining geometric dependencies and kinetic movement.

In Experiment 4, *Hyperboloid of One Sheet*, the geometric profile of the construction material was algorithmically encoded by defining the computational component. The construction and assembly mechanism of a particular material profile, namely a rectangular profile, was algorithmically encoded by constraining a geometric relationship in the geometric model.

### 3.6.3. Exploring geometric form integrally with manufacturing methods

Like materials, every manufacturing technique—additive (e.g., 3D printing), subtractive (e.g., milling), forming (e.g., CNC former)—has its own particular complexity that needs to be architecturally explored, described, and visualised. Through algorithm, the complexity of the manufacturing method is described in order to design, generate, and visualize the possible forms it can produce.

CNC machinery stands at the intersection of the theoretical and the empirical domains of design exploration. CNC machinery is the last output device of the digital continuum, translating geometric data into the mechanical motion of the machine and through this enabling the materialisation of the algorithm’s immediate outputs. The affordance of the machine and what it can do becomes important at the design stage, and is translated as a qualitative schema that then becomes a design driver and can be described in terms of algorithm.

![Figure 3.13. The figure shows that to explore form integrally with its materialisation, a qualitative schema must be developed for the empirical materialisation stage prior to the development of algorithms.](image)
Fabrication methods and material properties introduce constraints, which the designer must address. The design of a bookshelf (Fig. 3.14) provides an example. For this project, a generic Voronoi algorithm was used as a source of inspiration to explore a formal design idea. The Voronoi algorithm represents and visualizes a pattern found in nature computationally by unravelling the logic behind its pattern through algorithm and regenerating it as a geometric output. To make it architecturally relevant, the generation of the visual pattern was informed by the properties of the material to be used as well as by the method and cost of fabrication. Many questions arose that related the generated pattern to material problems, which then led to part-whole rearrangement and significant design invention—for example, when material thickness was introduced to the design, the intersection of the Voronoi lines became a design challenge which the joint was designed to meet. The joint was defined as a parametric component algorithmically; once this new element was introduced, the hierarchy of associative geometries changed and was reformed.

The capacity of algorithm to expand the exploration domain from the theoretical domain of computation to the empirical domain of physical materialisation is examined in the four experiments conducted for this dissertation and presented in Chapter 6. In each experimental project, the concept of encoding design intentions using algorithm is exercised in order to explore the potential of this concept for design exploration. This is explained in greater detail in each experiment.

The main challenge has always been how to formulate and translate the information related to construction material and fabrication machinery in terms of algorithm at a formal level, so that the exploration is not subservient to production techniques. Design is “a process of active choice” (Shelden 2014a)—formal aspects need not be subservient to practical ones, nor practical aspects to formal ones, but it is the active choice of the designer that enables a meaningful abstraction of the material context in a logical-formal language and vice versa. A further question, which was raised in conducting the first experiment, Honeycomb, and addressed in subsequent ones, is whether it is advisable or even possible to reduce the design to fabrication constraints, as is usually claimed in the current discourse of
computational design (see Chapter 2). With *Honeycomb*, the author shows how the fabrication techniques afforded by digital fabrication tools, combined with the surface conversion techniques afforded by computer-aided design tools, are influencing the direction of design exploration towards a logical process and the designer’s mode of operation towards the use of a certain geometric language, while at the same time constraining the exploration at its very early stages.

When the synergy between computation and materialization occurs very early in the design process, it limits the design exploration to being primarily technical and logical (see Experiment 1, Chapter 6). When synergizing computation and materialization, the design process and the product are heavily influenced by the techniques offered by the design and production tools and mediums. However, design should not merely rely on the capacity of machines: design should also challenge fabrication, construction, and material capabilities. A further question that arose in the course of conducting the experiments is, how early in the process must the algorithmic description of form be informed by the aspects related to the materialisation so that it does not impede innovation (Fig. 3.15)?

A way to address the above problem and shift the design exploration beyond logic is to introduce physical modelling, using the hand as a *manual sector of activity* and extending the theoretical design exploration towards tactile and intuitive modes. To explore the design potential in such a way that it does not become subservient to logical operations while still considering the constructability of the explored form, the author suggests certain types of physical activities and techniques of making. Designing through small-scale handmade models is of a different nature than designing with primary consideration given to the construction material; likewise, the modes of physical making in the manual sector are of a different nature than geometric modelling and automated making by means of CNC machinery. By selecting physical modelling materials with respect to the constraints of the materialisation stage, it is possible to incorporate those constraints into the exploration in another way. The designer is challenged to select physical modelling materials that incorporate constraints into the exploration, and to find meaningful bonds between the handmade model and the CAD model, so that the handmade model has an effect on subsequent design stages. This is explored in Experiments 2, 3, and 4. However, working with physical modelling materials has its own limitations, and there are many things that cannot be explored with material in the real world that can be explored virtually through algorithm. A question that arose while conducting the experiments, particularly with the last one, was
whether working with handmade physical models really does impact the quality of the exploration and benefit the designer in their exploration.

When working with handmade models, at some point the designer will want to bring the early physical modelling exploration into the digital world. To do so the designer must choose a way to digitally, geometrically, and parametrically represent the physical models. Algorithms enable this process, and the designer has to define particular parameters and geometric dependencies by means of algorithms. This translation must enable the interesting and relevant findings from the manual sector of activity to be regenerated in the CAD-computational sector. It is important that the chosen parameters enable the exploration that has taken place in the manual sector of activity to continue once it moves into the computer environment. At this stage, the designer explores a spectrum of design possibilities while parameters are changed.

Experiments 2, 3, and 4 examine different ways of enabling the manual sector to interact with the integral computation and materialisation sector. To create the continuity of the manual exploration, Experiment 2, Strip, uses a technological interface to create a bond between the two sectors of activity. Similar to CNC machinery, which is an interface between the digital computation and materialisation sectors, devices such as 3D scanners or sensors can act as interfaces between the manual sector and the digital computation sector. These input devices translate aspects of the physical world into data that can be read by a computer. In Experiments 3, 4, and 5, the bonds between the manual and computation sectors are created by means other than these technological tools.

### 3.6.4. Mediating between different scales of material practice

Design exploration in the context of architecture as material practice means not only that considering aspects of the materialisation stage is an intrinsic part of form definition and design, but also that the designer is engaged in working with material as an integral part of the design process and for the realisation of the design idea itself. The importance of physical making and material thinking points towards the challenge of scale. For every scale of making and working with material, there is a particular knowledge with which designers can explore design possibilities. For instance, the knowledge about every detail that is important in the constructability of the large-scale product is of a different nature than that of physical model making at the earlier design stages (Shelden 2014b).

The knowledge about details important for the construction, fabrication, and assembly of a building belongs to the materialisation stage and revolves around large-scale construction. Enabling the understanding of how these details are "going to look and feel as part of tools that the designer has to work with" gives a richer potential for designers to explore design possibilities (Shelden 2014b). However, considering every detail of constructability when exploring design through physical modelling and material might distract the designer from the creative exploration. In this case, there is a tension between the desire for bounding the exploration space to realisable forms and the desire for creative physical model making at early stages of exploration.

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69. Another way is to use algorithm in an explorative manner, rather than as a tool to describe the designer’s intention. (Personal discussion with Benjamin Dillenburger, September 2015, Toronto, Canada.)
When Frei Otto designed the West German Pavilion for Expo 67 in Montreal, the knowledge related to building, construction material, construction methods, and details used in the latter stages of the design process was of a different nature than the knowledge he used in the generation of the soap-film models in the early exploration stage. As result of unsophisticated design tools, the development of the exploration model was disconnected from form description and form realisation; the form was post-rationalised in order to be built with actual construction materials and techniques. And yet, dipping a wire frame in a soap solution enabled him to explore minimal energy forms and consequently enabled him to find and describe a geometry with the least surface area—if his early physical exploration had already incorporated the actual construction materials and details of the tensile roof structures, he would not have been able to estimate form generation in the way he did, and consequently his exploration would have been limited.

Algorithm allows the designer to encode aspects of materialisation into the exploration domain, and to take relevant findings made within the manual sector of activity and digitally and parametrically represent them in the CAD-computational model, thus continuing the exploration that takes place in manual sector of activity (Fig. 3.16).

In Experiment 1, Honeycomb, it is possible to see the shift that takes place in the physical exploration as material changes towards the materialisation stage. In this experiment, the use of paper as a physical modelling material allowed the logic of the overall form, which is double-curved, to be resolved easily by creating folds and cuts in the paper. As result of its scale and material properties, paper had structural advantages for manual exploration that the construction material did not have. However, to explore and ultimately produce the same overall form with construction materials, the logic of the form had to be resolved with discrete plates and joints which had to come together at precise angles (Fig. 3.17). Similarly, in Experiment 3, Hypar, in which two scales of physical modelling were used, one with paper and one with concrete, the knowledge involved in the folding of paper is of a different nature than the knowledge needed for casting the components, which required the production of a stable mould that would allow the designers to quickly and easily explore the variants of a form.

When working with handmade physical models, the designer will at some point want to get these explorations into the digital world. The designer has to choose a way to digitally, geometrically, and parametrically represent a physical model. Algorithms enable the representation of physical models parametrically and digitally, and then geometrically as the algorithm is executed. Using algorithm, the designer defines particular parameters and geometric dependencies. This translation is done in a way that enables...
Every discipline sees the physical world through its particular lens. An example is a bent piece of paper: generally speaking, a designer who is bending a paper strip is not interested in the density of the fibres at every bend but in the curvature of the bend. It is important that the chosen parameters enable the continuation of the exploration that has taken place in the manual sector of activity when moving to the computer environment. Once the physical exploration is represented through algorithm, the designer can explore a spectrum of design possibilities as parameters are changed.

The use of algorithm allows the designer to explore form freely while retaining the possibility of extending the physical exploration digitally and parametrically, and to mediate between different ways of making and between different scales of material practice. By mediating between these stages, the algorithm not only links the early stages of design with later material problems, but also negotiates between their capabilities. Since the digital geometric model generated by the algorithm is scaleless and immaterial, it enables explorative operations regardless of real-world constraints; at the same time, it has the capacity to parametrically constrain the geometry to perform according to the capabilities of construction materials. Algorithm thus allows the simultaneous representation of different scales of material practice in the exploration.

Experiment 2, *Strip*, shows how it is important to be able to explore form freely and at the same time retain the possibility of extending the early physical exploration towards the materialisation stage. The range of scales of making and material practice at which the design exploration took place in

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Footnote: 70. Every discipline sees the physical world through its particular lens. An example is a bent piece of paper: generally speaking, a designer who is bending a paper strip is not interested in the density of the fibres at every bend but in the curvature of the bend.
this experiment includes two extremes: the manipulation of the paper strip for early physical modelling and the lamination of wood strips employed in the production of the large-scale prototype. Paper can be manipulated easily by hand, enabling an exploration that would not have been possible with the construction material. However, the manipulation of the paper strip and the lamination of wood strips entailed very different processes of making. Algorithms were used to represent the paper strip parametrically as a digital developable surface; the deduction and generalisation of the early physical models through algorithm enabled the domain of design exploration to be informed with influential parameters from both the early physical modelling and later large-scale prototyping, allowing the designers to create negotiations and correlations—that is, to create a technical bond—between the two levels of making. This creation of a technical bond leads to significant invention.

The diagram below shows how algorithm mediates two scales of material practice (Fig. 3.18). If we know our construction material is a strip of wood, we can encode its maximum curvature into the exploration algorithm that relates to the paper strip. Here we can physically twist and bend the paper and explore formal propositions. Once we scan the geometry of the desired curvature, the algorithm can compute and generate the approximate possibilities, ensuring that the curvature produced will be realisable using wood—if it is not, then either the physical model must be reworked, or a different construction method developed for its full-scale counterpart. One could say that the computer and algorithm on the one hand help us explore the relations between detail and whole, and on the other hand enable a more tangible exploration through physical modelling, in which the designer can still explore the constructability of the exploration. Generally speaking, while the early physical exploration benefits from the flexibility of the material to fold, twist, and bend, materialisation entails discrete parts that will not allow this kind of free exploration.

In Experiments 2 and 3, the choice of paper as a modelling material was based on a set of building intentions. These intentions may be described as constructability requirements in the computational form. While working with a paper strip constrained the exploration to forms that could be constructed from sheet material, the algorithms employed limited the exploration to forms in the Euclidian space of the computer that were constructible given the fabrication constraints and construction materials. In Experiment 2, prior to the search for an algorithm the designers correlated the design problem to a geometric and mathematical model—a developable surface—suitable for representing a paper strip. That is, when translating the paper strip into the digital world, while a certain set of algorithms had to be chosen, it was necessary to first choose a model that would meet the requirements to solve the problem.

3.6.5. Creating interdependent links between different models

By creating interdependent links between models and expanding the exploration domain to a hybrid digital and physical one, new insight can be gained.

In the expanded digital-physical exploration model design intentions are not captured and represented by a single model, but by disparate sets of physical and digital (computer-based) models. The integration of material, form, and forces is an innate property of a physical exploration model, as in Otto’s soap-film models, in which gravity was integral to the exploration of form because the environment for the exploration was the real world where things work together seamlessly. A geometric form that is created and defined in a CAD geometric model, however, does not automatically integrate information related to material: materiality is not an innate property of a geometric form, nor is such a form automatically affected by external forces (gravity, wind, etc.). The designer must abstract and for-
mulate these things and introduce them into the exploration model as design parameters and as influential factors that, when changed, alter the geometric form.

Design exploration by means of digital design and fabrication tools entails two modelling environments, physical and digital, in which disparate sets of physical and digital models—CAE analytical expert models, CNC-fabricated physical models, hand-made models—are developed along with the CAD-geometric model to capture and represent various intentions (e.g., geometric form, environmental forces in the context of the future building, manufacturing methods in the context of production). For these models to interact with one another and work together towards the same end—for them to produce a combined effect greater than the sum of their separate effects—the designer creates links between them. Using algorithms and computation in design exploration enables the designer to create informing links between disparate sets of models. The term informing links is used here to mean links that represent informing relations, in the sense of driving the input of one model or instance with the output of another; in order to incorporate the models effectively in an exploration model to impact the exploration and lead to new discoveries, the models have to be linked to one another in an informing and generative manner.

The kinds of informing links enabled vary, and these variations depend on the nature of the different instances used in modelling and models that are connected by means of these links. Using the computer and algorithmic tools to expand the design exploration and examine new interdependencies between models and instances, this research identifies three kinds of informing links: one-directional, circular, and bidirectional ones.

One-directional informing link

Using the computer and algorithm, “a direct link from design through to construction” can be created—what Branko Kolarevic refers to as a “digital continuum” (Kolarevic 2003c, 2). As Kolarevic notes, this continuum is made possible by the “use of digital technology as an enabling apparatus that directly integrates conception and production” (Kolarevic 2003c, 3). In this continuum, the CAD-geometric model serves as a core model and point of coordination between the individual models involved in a project. It must provide the geometric model for CAE expert analyses, for example, as well as geometric information about the parts and machining instructions for fabrication (Fig. 3.19). The computer provides common ground and a direct link between the CAE and CAD models, where information can be exchanged using a common data set—0s and 1s. Using digital output devices such as CNC fabrication machinery, a computer-generated physical model can become part of digital continuum.


72. In this regard, in addition to her own learning from the experimental projects, the author examined a number of case studies in practice. An example is the case of the Basra Main Stadium by 360 Architecture. The author interviewed Jonatan Schumacher, Director of Advanced Computational Modeling at Thornton Tomasetti. Thornton Tomasetti was hired by 360 Architecture to reduce the fabrication time of skin panels for the stadium by eighteen months and investigate whether it would be possible to achieve an aesthetically pleasing result from only five different moulds. Digital Project (DP) software, based on the CATIA platform, was used to create the geometric model to develop the panels. “Using this advanced parametric modelling software would also allow the engineers to maximise control over the complex surface geometry of the GFRP panels” (Schumacher and Otani 2012, 233). As Schumacher and Robert Otani mention in the paper “Advanced Computational Modeling in Multidisciplinary Design,” “throughout the design process, the DP model also served as a coordination model between the individual consultants involved in this project” (Schumacher and Otani 2012, 234).
However, the digital continuum, as a continuous chain in which adjacent models are connected to one another, only enables a one-directional link between disparate sets of models, from computer-aided conception to production.73

Circular informing links
Algorithm allows the designer to link models in ways that shift the exploration beyond linearity and enable the integration of knowledge in a non-linear fashion. What is produced in and belongs to the latter stages of the design process is fed back to earlier stages to inform the earlier models.

The integral exploration of form with respect to materiality demands early contributions of expert knowledge that allow the designer to explore architectural concepts and design options at the conceptual stage in an integral manner. “Linking the output of a system with its input in a circular fashion is referred to as feedback” (Tessmann 2008, 44); a feedback loop allows the designer to incorporate expert knowledge at the conceptual stage and simultaneously explore design alternatives. To enable a feedback loop in the exploration model, circular informing links between models are created by linking the outputs of each model in the chain back to the former models as an input in a circular fashion (Fig. 3.20). While the CAD-geometric model is the core model, it is not the only driver of the exploration; the subsequent models in the chain can also act as drivers of the exploration model. For example, by circularly linking analysis results to the former CAD-geometric model, the analytical model can drive the CAD-geometric form.

To expand on the informing link, the question is how exactly does algorithm provide these circular links in the exploration? How is it different between the different instances and different kinds of models? Are all of these links algorithmic and automated, or do all require a human to observe and then act upon the former models—changing the parameters or the concept, for example?

Automated feedback loops between digital models
In a digital exploration model, automated algorithmic feedback loops can be created to develop form with reference to the context of environmental forces (Fig. 3.21). Cooperation between the CAD-geometric model and CAE analytical expert models in the formation process is not new, and has been used in several areas of focus in architecture, such as form finding. In this research, the analytical model is not merely employed for analysing the geometric model, but rather is generative and informative.74 This allows for the exploration of possible forms in the context of their environmental forces.74 In such an approach, expert analytical models are used to generate information that drives and alters the geometry, topology, and dimensions of ensembles within geometric models, rather than merely analysing already designed geometry. Expert analytical models produce one output dataset for each iteration. When the CAE analytical expert model is used in a generative rather than purely analytical role, the attempt is to derive the topology and geometries of the geometric model after every iterative feedback loop. The geometric model is linked directly to the analytical software to provide the basic geometry for the analyses, and the results are fed back
Conception can be with the aid of computer, or with models or artefacts that are not necessarily digitally based.

In the computational design field, the term *generative* is commonly used to emphasise the use of analytical expert models in the exploration and design process in ways that make them drivers of form exploration, rather than merely being tools for post-rationalising the form. For example, Kilian speaks of “the use of analytical engineering principles in a generative manner for design exploration” (Kilian 2006, 47), and Oliver Tessman writes that “the capability of the method to simulate physical behavior is used to turn the analytical tool into a generative one by circularly linking analysis results to generative procedures (Tessmann 2008, 144–45).

For example, see Kilian’s use of the Finite Element Method to create a range of simulations as a design driver. As he notes, “in contrast to conventional FEM analysis the FEM is used to generate a design geometry and topology” (Kilian 2006, 45–56).

This would allow live feedback of the changes made.

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76. This would allow live feedback of the changes made.
currents of the site (Fig. 3.22). To investigate the capacity of algorithm for enabling interdependent circular informing links between digital models in a generative and informing manner, the following expert analytical models were developed and used, interpedently linked to the CAD model:

A wind model was created using ANSYS CFD simulation software to predict the impact of wind and snow flows on the designed geometry, and consequently inform the configuration of the surface geometry;

A material behaviour and structural model was created using the Abaqus FEA software suite for FEA and CAE to alter the geometric form based on its behaviour when structural and material properties were assigned to it.

In practice, this process was not a very smooth one. It is important to keep in mind that while an automated link was created, there were still many decisions that the designers had to make, which kept the process of design far away from full automation.

Interpretive feedback loops

Not all circular informing links are algorithmic and automated: some are created by a human observing, evaluating, and then acting upon the former model and modifying the algorithm that describes the geometric form. Interpretive feedback loops can be created to explore geometric formation simultaneously with its empirical materialisation. A circular informing link is created that runs from the digital geometric model all the way through to computer-generated physical models and back into the geometric model. For computer-generated physical models to go beyond merely being final products and instead become drivers of design solutions, the designer must analyse them and feed the results back into earlier (CAD and CAE) models in the chain, modifying them. This is a not an automated feedback loop, but rather an interpretive one (Fig. 3.23).
The exploration of geometric form was interdependent with the force contexts (wind and gravitational force). The primitives of the geometric models were altered by the expert analytical models so that they could assume the configuration that best fit the wind and snow conditions around the object while remaining sufficiently stable to handle its dead load.

Algorithms facilitate the creation of these links by providing the designer with a platform for encoding constraints when making the form definition, enabling persistent regeneration of outputs, materialisation of outputs using digital fabrication tools, and modifications at all times and after every evaluation of the results. The designer evaluates the empirical results and modifies design parameters—interpolating the algorithm and, if necessary, modifying the concept—and then executes the algorithm that will regenerate the outputs. This requires the designer to encode the constraints and underlying principles of construction material, fabrication, and construction when making the design definition, and also requires persistent materialisation using digital fabrication tools and feeding the designer’s evaluation of the result back to the form definition to refine the design iteratively. This interpretive feedback loop is enabled by human-algorithmic circular informing links.

The role of the computer-generated physical model in the design process is not that of a final product but that of a tool to enhance conception. To perform this role, computer-generated physical models must persistently feed back into the earlier models that enabled their creation. In a complete cycle of concept and production, a computer-generated physical model would be made for every design cycle and fed back to the associated model as a design solution. The computer-generated physical models are not created as final presentations of the CAD-geometric model, but rather are part of a circular recursive loop.

With algorithm enabling feedback loops in the design process and design exploration increasingly influenced by feedback loops, the traditional linear process of ideation—idea to project to product—is being replaced by a nonlinear process. Feedback loops enabled by circular informing links put the emphasis on a live trial-and-error approach to working in and thinking about design: “Designing buildings or structures can be described as a process comprising the analysis of a problem, the synthesis of a design proposal and the evaluation of this proposal. This ‘trial and error’ process is conducted in a feedback loop until a satisfying solution is developed.”

77. The exploration of geometric form was interdependent with the force contexts (wind and gravitational force). The primitives of the geometric models were altered by the expert analytical models so that they could assume the configuration that best fit the wind and snow conditions around the object while remaining sufficiently stable to handle its dead load.
Searching for these end results and synthesising them into an algorithm of computational form, as well as evaluating them by executing an algorithm and feeding the result back into the ideation stage, can be seen as a way of expanding the theoretical design domain towards the empirical domain of machines, material, and construction.

**Bidirectional informing links**

The feedback loop mechanism does not allow the designer to reverse the links between design representations of the models once the links and the direction of information flow have been set. They remain the same throughout the exploration, so the roles of driver and driven, once given, are not reversible. By creating a bidirectional link, a greater degree of integration and interdependency between the models and their design representations can be created. Bidirectional links allow the designer to reverse the dependencies, translation, and information flow between the various domains, representations, and models involved in an exploration. Axel Kilian defines bidirectionality as the “ability to reverse the link between design representations”; he describes it as “domain-independent,” and says that “it can be enhanced through computational and physical constructs. . . . By adding bidirectional properties to the translation between different design representations, design exploration can support even complex constraint dependencies” (Kilian 2006, 22).

The use of algorithm and the parametric-associative system alone, as the only mediums in an exploration, does not allow the designer to create bidirectional links between different models. As mentioned previously, the use of algorithm in the exploration is strongly tied to the application of the parametric-associative system, and the current parametric-associative dependency tree allows the propagation of effects only from the parents towards the children: changes in the child do not affect the parent. Thus the use of algorithmic tools alone for design would only allow a one-directional flow of information and propagation of changes.

Kilian cites Ecotect, commonly used as an analytical tool for lighting, acoustics, and energy analysis, as an example of computer software that can provide design exploration with bidirectional links. As he notes, Ecotect “has features that allow the reversal of the design direction”; for example, it “is possible to calculate the accumulative shadow created by a window shade over the course of a year,” and “in reverse it is also possible to generate such a shading device from the constraint to cast shadow on a specified window opening.” For Kilian, this “illustrates a fundamental shift in the design process: the reversal of driver and driven in design exploration” (Kilian 2006, 40).

The algorithmic tools in CAD software still do not facilitate bidirectional links. However, by bringing the designer into the exploration domain once again, a manually interrupted bidirectional link can be created. Since the parametric-associative system does not allow for bidirectional dependencies, the designer and manually made physical models are introduced into the exploration model to overcome this limitation.

Experiments 4 and 5, *Hypar* and *Hyperboloid of One Sheet*, use bidirectional links—ones in which different design representations have equal influence—to augment the exploration. In these experiments, handmade physical models are incorporated in the exploration model. The cooperation between the designer and the digital and physical models is exercised by creating a bidirectional link between the digital and physical models. Using bidirectional links in these experiments, representations in the digital and physical models are given equal power in driving the exploration, and neither representation is subservient to the other: the two design representations alternate in the roles of driver and driven.
Creating a bidirectional link allows the designer to shift the role of driver and driven between design representations. Pushing the idea of bidirectional links between physical and digital models, is it possible to envision a future development in which a direct, live link between models would be created, so that we could alter the digital model by interacting with the physical model.

3.6.6. Reciprocal reformation of design and the designer’s intention

Given that algorithm enables the designer to create informing links and interdependencies between disparate sets of models and design representations of models, the question is whether these informing links are built into the overall process from the start or evolve in the process of a project? How do these links lead to changing the design parameters or the design concept, for example?

An algorithm that generates geometric form is flexible and receptive to change, and is open to significant alteration. After every feedback loop the resulting solution for the primary problem leads to a bigger problem and question. Consequently, as design proceeds the algorithm network is interpolated and evolves and changes as a result of the loops created between the algorithm and the digital and physical models.

Today, as a result of the application of algorithm in CAD, the CAD-geometric model is sophisticated enough to be informed and reformed, and to inform. “Currently, parametric CAD software offers sophisticated three-dimensional interactive interfaces that can perform variations in real time, allowing the designer to have more control and immediate feedback when a parameter is changed” (Hernandez 2006, 311). In the experimental projects conducted, the design team used Rhinoceros and Grasshopper to create the geometric models. The programmatic nature of Grasshopper allowed the designers to descriptively define the rulesets that generated the geometric models, then connect the relative parameters of the ruleset to expert analytical models iteratively for continued live analysis in an informative manner, then generate the geometric configuration.

In a full conception-to-production cycle, every time an algorithm generates outputs and the designer evaluates them, the designer’s intention evolves and the algorithm is interpolated and evolves as well. It is the designer who, by creating meaningful informing links between the models—for example, feedback loops between later and earlier in the digital continuum—examines new interdependencies in the design exploration and provides a productive exploration. The first instance of the CAD-geometric model that a designer creates to conceptualise an idea does not represent the final product in its totality; rather, the designer makes choices in interdependently linking the CAD-geometric model with other models in the exploration using one-directional, circular, and bidirectional informative links between them so that the CAD model matures and is iteratively altered. In the conception-production-reconceptualization cycle, the CAD-geometric model evolves and undergoes constant reformation as it receives feedback from subsequent models in the chain. The digital con-

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78. The design and building of a computational form is a situation in which the solution to design intent depends on solutions to smaller parts of the same problem (such as the possibility of fabrication, material capability, and constructability). This is also known as a recursive process, in which the answer to the problem at hand depends on solutions to smaller parts of the same problem.

79. The driver is the one influencing, and the driven is the one being influenced.

80. Kilian adds that “in the ideal case of a bidirectional exploration the products of the exploration can become the starting point of redefining the exploration itself” (Kilian 2006, 304).
continuum entails a recursive chronological move from the conceptualisation of the idea by means of the CAD-geometric model, to the reformation of the geometric model based on the CAE expert model, to the reformation of the CAD and CAE models based on the computer-generated physical model (Fig. 3.24). In every complete cycle, the CAD-geometric model progressively increases in detail by virtue of the feedback it receives; consequently, the computer-generated physical models tend to progressively increase in scale and detail. The incremental scaling up of the physical models in successive versions takes us ever closer to design resolution. Experiment 1, Honeycomb, exemplifies such an exploration model in practice.

Figure 3.24. The diagram is developed from Experiment 1, Honeycomb. It shows that prior to any expert analyses the design team has to make the proposal of the 3D geometric model. This entails selecting the primitive (i.e., surface or curve) and designing how this primitive can be positioned in relation to each others and the whole object. Therefore even when form is generated from the synthesis of analyses, the spectrum of forms that can be explored with the generative approach relies on the way the designers initiate the design and the relationships between design elements.
3.7. Reflections

Algorithmic design tools, such as Grasshopper, present things to the designer’s eyes that it would not be possible to visualise with pencil and paper, and also enable live and iterative changes to possible outputs as design parameters are changed. In that sense, an algorithm can be seen as an abstract machine that enables the generation of outputs. Using algorithmic design tools, the designer creates a generic parametric-associative logic of form that ultimately generates the geometric form. In return, the tools enable the propagation of the changes to the outputs when the designer changes design parameters. Thus the designer can explore the implications of changing design parameters in the outputs throughout the design process, expanding the visualisation of possible design outputs and the designer’s imagination.

Algorithm as a tool and computation as a method for design require pre-rationalisation of logics as well as the “structuring [of] the design approach early on in the design process” (Kilian 2006, 54). One might argue that consciously defining the logic of form and pre-rationalising the design process is not really exploration. It is true that designers consciously define relationships and rules based on their individual understanding of a design context and related design problems, however it is still exploration, as the mind is not capable of calculating and imagining every possible design output. When the designer executes an algorithm, it computes and generates a spectrum of possible forms that the designer would neither be able to conceive of in the mind nor to manually model, thus expanding the scope of the designer’s imagination. In this manner, all the possible variant forms of a particular associative-parametric arrangement of components can be explored. This way of designing enables the exploration of previously unimaginable spaces and possibilities.

The use of algorithms enables the designer to conceptually encode and automate certain techniques, processes, and information that belong to the materialisation stage in the early exploration stage by introducing parameters that stand in for tangible objects of empirical experiments. Besides enabling the designer to encode constraints and intentions, algorithm is a generative tool that enables an array of variant outputs that originate form the same formal logic, enabling the designer to reconceptualise an initial design intention. Initial design intentions can be visualised as well as materialised when coupled with CNC machinery, and the visualisation of a spectrum of forms and provision of geometric necessities for CNC production leads to making many physical models. A spectrum of physical and digital outputs is produced, and these outputs in turn impact the way the designer thinks. Through the evaluation of the iterative outcomes of algorithms, design intentions can be reconceptualised. The designer can then choose between physical models, explore and investigate design, and proceed with or modify the design.

The immediate outputs of algorithmic tools are numerical and logically founded. In the context of architecture as a material practice, CNC machinery enables the designer to get the algorithm’s immediate outputs out of the computer into the physical world. The resulting physical outputs enable the designer to evaluate the design not just visually and numerically, but based on tactile evaluation and the physical behaviour of material. Through the iterative feedback loop, the initial algorithm is interpolated and reformed in accordance with real-world constraints.81 There is a persistent circular loop between the restructuring of information and the rearrangement of material in space. Thus circular loops are created.

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81. Its generative nature combined with the feedback loop enables the evaluation of the iterative outcomes of the algorithmic process, connecting theoretical space to empirical space.
between the processes of reforming the algorithm’s structure, form generation, and materialisation. Materialisation and the rearrangement of form entail constant translation and abstraction, moving from the world of geometry to that of material and then back to geometric description of the construction material and tool affordances. This points towards the strong link that the author sees between the descriptive aspects of computer-aided generative and computational processes that use algorithmic tools and the empirical practice of materialisation processes that use digital production tools.

Design by means of algorithm requires the designer to operate in a contemplative and intellectual way. Pure employment of algorithm in the design process limits both the design and the designer’s operation to logical and numerical solutions at the expense of intuitive, physical, and tactile qualities. In the context of material practice, it is crucial to produce physical artefacts in order to move beyond the numerical and intellectual mode of operation. The digital manufacturing of the algorithm’s output as a physical artefact creates a shift in the designer’s mode of operation from the intellectual to the sensuous, and in particular to the tactile.

While the use of algorithmic modelling tools coupled with CNC machinery enables the designer to evaluate the results based on tactile and physical qualities, computer-generated physical models are still founded in logic and are of a different nature from physical models produced by hand. The outputs of CNC machinery are predetermined and definitive. The technical nature of algorithm propagates through the digital chain, to its immediate output as well as the digitally produced physical artefacts. Handmade physical models, on the contrary, are indeterminate and full of ambiguity, and therefore leave space for interpretation. The author emphasises the importance of synergising the integral computation and materialisation sector of activity with handmade physical modelling.

Physical activity is also valuable in the conceptualisation of design intentions at the early design stage. In creating and exploring geometric form using algorithm there is a need for significant cognitive activity. Moreover, compared to empirical methods, modelling with the aid of algorithms is a very selective mode of working. Creating algorithmic models entails pre-rationalising the design approach, and once the design approach is determined there is little flexibility in the process. The designer has to define ahead of time which geometric elements will be dependent upon other elements. Before it can appear on the computer screen, each geometric element and its parametric-associative relation must be well defined and described—that is, it is not a question of how to draw a line but how to describe it—and this requires a degree of formalisation prior to the creation of the algorithm that generates the geometric form. Since design ideas are not always clear at such an early stage, physical modelling and crafting enable the concurrent development of design intention and the underlying design intent.

Physical modelling helps formalise the design idea prior to the abstraction of the design intention as algorithm and the rule-based structuring of the design approach, but it is important to point out that the handmade physical model is not meaningful unless it performs a specific task in the process. In Experiment 2, Strip, for instance, the manual manipulation of curving paper strips is meaningful in the context of the design question that is being explored: the capacity of being fabricated from sheet material. Without this specific relation of material format, the handmade models would be disconnected from the exploration model and the rest of the exploration. At some point the physical exploration must be translated to a digital and parametric model, and this translation process entails both the reduction and the abstraction of the physical world. This poses two challenges for the designer: to find or
create an appropriate algorithm to represent the physical exploration, and to enable meaningful links between the physical exploration and computational modelling. This means that the beginning of computational modelling does not mean the end of the physical exploration, but begins a synergetic process (Fig. 3.25). This too is explored in Experiments 2, 3, and 4.82

While algorithm and the computer as they are used in architecture are very powerful in computing complex processes and generating outputs, the capacity for conceptualisation still lies with the designer. To conceptualise or arrive at an idea, the designer relies on knowledge and skills in both the numerical and material domains. It is the designer who gives agency to a design medium, thus the abstraction or emergence of an idea does not have to begin with algorithm: in many cases the idea emerges from material practice through manual modelling and playing with material, which can then subsequently be abstracted, developed, and represented using algorithm.83 Indeed, the argument here is that a computational method, here exemplified in terms of a generative algorithm, must not be the only method driving design, as it may limit the exploration to a merely technical, logical, and numerical exercise in which there is no place for intuition. The algorithm should be seen as an operational instrument of design that enables designers to encode constraints (performance criteria, material capability, and fabrication techniques) and initial intentions; it is an explorative tool for driving design, but it is not the only tool.

There is a significant difference between the material and numerical modes of exploration, and the material, tactile, and physical world has properties that drive the exploration beyond numerical thinking. The experimental projects conducted in this dissertation show that significant design invention occurs when synergising these two modes of design. As such, this research gives equal value to the material and numerical modes of exploration and demonstrates the importance of establishing informa-

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82. There are different modes of describing a surface digitally. In the case of the paper strip, it was done through scanning and for the algorithmic method of describing the developable surface the paper was represented and regenerated digitally. A physical thing can be regenerated digitally using many languages and methods; it was the design team’s choice to use algorithm, because it would allow for generative production. In the case of the paper, algorithm has an input and an output, and a body that leads to the generation of developable surfaces. In this case it was a matter of what sort of inputs the algorithm was to build upon and then how it would describe the strip based on those inputs.

83. It is possible, and indeed very common, to play with an existing algorithm as a source of inspiration. The author has tested this in her studio, and Benjamin Dillenburger has noted in conversation with the author that he has also examined this with his students.
tive links and meaningful interdependencies between the digital-computational sector of activity and the physical sectors, which involve CNC machinery and the hand in the process of making.

While there is a growing interest in using algorithms for incorporating the constraints and potentials of materiality as drivers in design exploration, this use has increased the quantity and kinds of information involved. It has introduced a level of complexity into the design exploration that surpasses the designer’s ability to predict the outcome and have comprehensive control over the design process. This in turn has changed the roles of the designer, design, and ideation and the relations between them. In this context, the exploration and ideation of a project cannot simply be resolved by conventional design methods. This chapter opens up the question of what methods are suitable for enabling the incorporation of the constraints and potentials of materiality as design drivers. What are the significant ways that algorithm can be used in design exploration so that incorporating engineering, fabrication, and construction knowledge goes beyond merely constraining the exploration and moves towards shaping the design idea and ideation? In the Experiments chapter, a number of synergic ways of employing algorithm in design that are relevant when considering material practice are exercised. In all of these experiments, algorithm as a generative tool is at the core of an exploration model in which many parts and sectors of activity can operate interdependently. It serves as a design medium and as a channel for integral form exploration that also ensures the materialisation of the design using digital fabrication tools. The hope is that this will enable significant design invention that can finally overcome the still prevalent separation of design and making and introduce new meaning and substance into the profession.
Material and geometry: Spatial design mediums
The previous chapter presented the significance of algorithm as a design medium and the ways that the application of algorithm in architectural design by means of algorithmic environments in CAD and 3D modelling software has allowed designers to expand the exploration model and test new interdependencies between disparate sets of digital and physical models. In this hybrid digital and physical exploration, the physical and digital worlds are becoming unified in one exploration model. The designer plays an important role, setting up the exploration model by selecting one medium over another and by giving different roles to the design mediums—for example using a strip of paper or developable surface algorithm (or both at the same time) to incorporate planarity as a constraint of sheet material into the exploration and to compute form. By selecting one medium instead of another, the designer creates an entirely different exploration domain that leads to different results.

Algorithm, as it is applied in architecture today, together with mathematical formulas, as a medium for design, is a logical medium and operates based on reasoning. If it is used for design representation, algorithm is an objectless proposition, meaning that it does not have the immediate figurative (visual and topological) character of the object it is representing; rather, it is the logic of what is to be empirically known. For instance, a vertical column could be described by an algorithm using the mathematical axiom \( y = mx + b \). In contrast to algorithm, geometric concepts (e.g., surfaces), and materials as mediums for design are spatial, and have the figurative character of the object to be known. Both geometric concepts and materials have an immediateness of insight when it comes to communicating the object of exploration; they present the spatial and imaginary character of the empirical object being explored. For instance, in the example of a vertical column as an end product, both a line and a piece of wooden dowel, as spatial mediums, could stand in for the column, and one could also represent it by using geometry to show the paths of forces.

Regarding the use of computational methods for design exploration and the preoccupation of CAD modelling with geometry, Axel Kilian suggests that perhaps it is time to move beyond mere geometry-based design representations (Kilian 2006, 299–300). The question is how to do so, and in particular how to do so without abandoning what has been and remains useful in geometry and conventional modelling. This dissertation proposes that rather than merely moving beyond geometry, we might embrace geometry as part of a complex exploration model that also encompasses algorithms and materials. It demonstrates the important role of the designer in making significant findings possible by choosing ways of conceptualising constraints using geometry, material, and algorithm and turning them into enablers in the exploration. Moreover, the use of the hand is lost in current processes of digital computational design and materialisation. Given that design is a process of active choice, this dissertation emphasises that the designer’s mode of operation and the exploration must not be limited to numerical and algorithmic (rule-based) means.

While geometry links the exploration with the designer’s integral visual and logical mode of operation, there are often important aspects of the design that go beyond visual appearance. Geometry does not provide integrated visual and tactile information in the way that material and working with physical models do. Working with material and producing physical models takes the exploration from being merely visual and imaginary to being tactile and tangible. This chapter will first describe the nature of geometry and material as mediums for design, pointing towards how the designer designs through them or by means of them. Second, it will present their potential for augmenting the exploration to embrace aspects of materiality as design drivers—material characteristics and geometric representations of materiality for linking the domain of exploration with material-world problems.
With respect to the overarching concern of this research—augmenting the exploration in the context of materiality—this chapter attempts to

- present the potential of geometry and modelling materials to inform the designer's mode of operation, the design intention, and design methods and processes;

- present how architectural ideas are defined through the selection of certain geometric concepts or modelling materials prior to construction;

- identify how material constraints can be conceptually incorporated into the exploration model through the selection of certain geometries;

- and identify how constraints related to the materialisation of the full-scale building can be incorporated into the exploration through the selection of certain physical modelling materials.

Although material and geometry are presented separately, the aim is not to separate them from one another in practice. In fact, in the hybrid digital and physical exploration model they work together to the same end.

4.1. Material as a medium for design

Whether small-scale or large-scale, the significance of physical models is in their materiality and physical existence. They are “engaging objects,” embodied objects, and may act as performing objects. On the one hand, “physical models supplement the designer’s mental models” (Viswanathan and Linsey 2011, 597), while on the other hand they fix the design and reduce the variety of ideas (Viswanathan and Linsey 2011, 590). Working with physical models entails working with material. Material is tactile: it is not definitive or perfect. It always computes and records its state of equilibrium in relation to forces. It occupies space and possesses a resting mass. A material thing contains a physical substance that is distinct from the mind. Manuel De Landa presents two things that identify the “mind-independent” object, or object that has an identity independent of the mind: properties and capacities. Materials such as paper, cloth, and wood, like any other material thing, have properties that, as De Landa notes, can be listed, and capacities that can be exercised (De Landa 2014).84 A material thing such

84. Note that an algorithm is more than a mathematical formula.

85. “When looking at an object while exploring and manipulating it with the hands, visual and haptic senses provide information about the properties of the object” (Aman, Lu, and Konczak 2010, 76).

86. In his talk at the What’s the Matter? conference, De Landa makes a distinction between “capacity” and “properties,” stating that a property is “real” and “actual” at the same time. The author’s discussion of cloth in this section is adapted from De Landa’s example of a knife, in which he notes that a “knife has a capacity to cut things. The capacity of the knife to cut is real, and if you use it then you exercise the capacity if you don’t use it then you never exercise the capacity. Capacity can be real without being actual. . . . The same knife can cut, kill, or murder, without the knife being changed, but only changing the thing it is interacting with. What capacity shows is that the world is open” (De Landa 2014).
as a piece of cloth has certain properties, such as weight, length, thickness, and density of fibres, and has certain capacities, such as the capacity to take on certain forms while resisting others.

Unlike a property, which categorises the enduring state of the material, its capacity is not a state but an event (De Landa 2014). By the active choice of the designer, a cloth can be folded, stretched, and formed: the event is both to fold and to be folded. It is a bidirectional dialogue between the designer’s hands and the material. Because material is mind-independent, having properties and capacities, it guides the designer in the act of modelling according to its capacities. A material binds the designer and the exploration to its capacity. When a machine mediates this dialogue, the act of exercising the material does not directly and immediately guide the designer.

Unlike a property, which is actual and real at the same time, a capacity can be “real” without being “actual”; it becomes actual only when it is exercised (De Landa 2014). The material’s capacity is waiting to be exercised and it is the designer who exercises it. For example, as long as the designer does not fold the cloth, the capacity of the cloth to fold, however real, is not actualised. Similarly, when CNC machinery mediates the exercising of a material, the dialogue between the designer’s hand and the material is shifted. Here the capacity of the material is only exercised when the machine’s tool head interacts with the material: the capacity of cardboard to be cut halfway through by a laser cutter, for example, is only exercised when the laser burns away the material from the cardboard. As De Landa suggests, by exercising the material’s capacities, without necessarily changing its properties, it is possible to explore the abundant possibilities offered by a particular material. The same cloth can be folded or stretched without being changed; rather, what changes is the spatial quality surrounding the material. The cloth interacts with space and forces, and the space of design possibilities grows as new capacities are explored and exercised.

The exercising of a material’s capacity is directly related to the ability of the hand and the affordance of machinery to exercise it. We cannot bend a log by hand, and cutting glass is not an affordance of a CNC laser cutter. Therefore, the selection of material always involves a concern for the scale at which a thing is made, the designer’s ability to manipulate the material, and the machine’s ability to machine it.

4.1.1. Ways of working with material in the design exploration

Generally speaking, three-dimensional physical models appear in different roles and at different scales in the process of design (Porter and Neale 2000, 19). By assuming new roles, these models push the design process forward (Porter and Neale 2000, 20–31). They can take the form of conceptual models, site models, design development models, massing study models, structural models, test models, presentation models, full-scale prototypes, and so on. In the course of the design process, physical models tend to increase progressively in scale and detail. Every successive scaling up of the physical models brings us closer to design resolution (Porter and Neale 2000, 19).

Concerning the role of the designer in relation to manipulating material, this research identifies three ways of physical model making that are relevant to the hybrid digital and physical exploration domain: one that is direct and intuitive and involves the human hand in the process of making, one that is mediated by machines and involves CNC machinery in the process of making, and, lastly, one that is a synergy of human and machine operation.
The hand versus the use of CNC machinery
With the use of the hand, the direct dialogue between designer and material through the intuitive and bodily act of making enables an immediate binding of the designer’s intention and the material’s capacity. The designer’s intention informs the material through the act of manipulating it; in response, by resisting certain events and enabling others, the material directly informs the designer’s intention and suggests new directions of development that were not apparent to the designer in advance. As the designer interacts with the material towards an intent (target form), the initial intention is continuously reformed as a result of the material’s capacity. The operations of conception and making are integrated, which keeps the development of the design intention and its exploration in synchronisation.

When a machine mediates this dialogue, the act of exercising the material does not directly and immediately guide the designer and the intention. Ordinarily, in current practice, digital fabrication tools such as CNC milling machines and robotic arms are used as pure extensions of CAD and the computer-aided design sector of activity—that is, of computation and computational geometry: CNC machinery is used to materialise preformulated computational geometric forms. The computer files provide explicit information for the mechanical movements of robots and other CNC machinery for the production of physical models (e.g., 3D-printed or CNC-milled models). Information varies from the geometry of an object’s parts, to the machining tool path, to speed, to precision.

Dennis Shelden notes that “CAD modelling strips away ambiguity, producing definitive geometric forms that ‘leave little to the imagination.’ These digital, logically founded constructs stand in curious contrast to the indeterminacy of physical based activities and artifacts” (Shelden 2002, 23–24). One may ask whether the production of large-scale physical models using CNC fabrication tools, as a direct product of CAD, can be an explorative activity, and whether coupling this sector of activity with computation can augment design exploration, the designer’s intention, and the conceptualisation of design itself. For the author, then, the question is this: how can one use these digital fabrication tools to have a creative or generative process, as well as to generate design ideas?

When designing with the ultimate intention of realising a building, at some point the exploration has to meet the affordance of the construction materials and the fabrication and construction methods for that building. The use of CNC machinery and robots as an integral part of the design exploration and the production of 1:1-scale prototypes can be seen as attempts to address and incorporate issues of manufacturability and constructability into the design exploration. The digital fabrication sector enables empirical exploration through physical models, from small scale to large scale, and the fabrication and construction methods that are imposed by the digital fabrication technology in this sector can be seen as mirrors of those imposed on the actual building.

Digital fabrication tools can be used in a way that provides insight into the real-world requirements for the realisation of a design proposal. They can be seen as a means of incorporating manufacturability concerns into the exploration domain. Making the CNC manufacturing sector integral to the exploration domain forces the designer to think through the different manufacturing steps, and may cause the designer to make design changes. Manufacturing and construction problems, which are not very apparent in CAD-geometric
or manual physical models, appear during the fabrication and construction of the physical prototype. Constraints such as the cost of construction material and fabrication, too, may force the designer to find solutions that are cost-effective in order to realise designs—sometimes the search for a fabrication solution and a less expensive way of building results in significant findings and design invention.

In contrast to CNC models, whose existence in the design process depends on computer models, handmade models are free movers. An advantage of working with manual physical models is their freedom and independence from other digital and physical models in the digital chain. Since their existence in the design process does not depend on computer models, they can freely appear at any stage in the design process and support the exploration and testing of different issues. They can appear prior to the CAD stage, in parallel with the CAD stage, or in parallel with the materialisation stage, which makes them a good tool for testing and exploring ideas, problems, or issues quickly and intuitively. Twisting a strip of paper, for example, is a way to quickly explore the forms it can suggest; similarly, tensioning strings along a simple wooden frame is a way to test the forms they assume in relation to the structural performance of the string network (Fig. 4.1). On the other hand it is important to point out that the freedom we have in exploring by way of the hand, which is true for manual models, has its own limitations.

It is crucial to remember that for manual models to be a meaningful part of the exploration, the designer's intention must already be embedded in them through the kind of modelling material selected. As such, the exploration model receives feedback and is constrained.

Synergy of hand and machine

Though human-robot interaction for exploration is beyond the scope of this research, it is important to point out that today, with the development of sensing and adaptive behaviour programming for robots, there is some research in robotic fabrication in architecture in which the use of robot arms as digital fabrication tools is seen as more than a pure extension of computer-aided design or mere output device for the materialisation of preformulated computational geometric forms. Rather, robots are programmed and equipped with sensors in a way that makes a collaborative human-robot exploration, in which designers work together with robots, possible.88 It is conceivable that one could push this idea to create an exploration model in which the designer works together with a robot in a human-robot-CAD circular informative loop to generate geometric form (Fig. 4.2).

In this regard, the critique of the use of the digital fabrication machinery as merely an extension of the computational sector—that is, exclusively as a tool to fabricate a predetermined design intention—suggests the possibility of using digital fabrication tools directly as a means for the exploration and generation of design ideas. Instead of creating the geometry of parts in CAD to be manufactured later using a robot, for example, the designer could “use CAD to make a line which stands in as a force vector for a robotic arm to bend a piece of wood to a certain degree”—thus the resulting geometric
form “is actually, then, the combination of the force vector and the material resistance,” which can be sensed and fed back to the CAD model. In this example, the geometric form is generated as a collaboration between human, robot, and material.  

While this dissertation makes a distinction between handmade models and models made with CAD and CNC machinery, the aim is not to separate them. Rather, the goal is to create a bridge spanning the designer, machinery, and algorithms. However, to create a bridge one must first know the different territories—thus while manual and CNC-generated physical models are presented here as distinct types, the ultimate aim is to speak about the design exploration model as a whole, and how these conventional models integrate with each other.  

4.1.2. Augmenting the exploration with material characteristics

Architecture as a material practice involves considering materiality throughout the design process. This means paying careful attention to materials and ways of physical model making, and their relation to the set-up of the materialisation stage for the actual building: the capacities of construction material, the affordances of fabrication tools, construction and assembly logic, transportation, and economy. In practice, this set-up is not always determined at the early stages of design—indeed, in most cases, decisions about the kinds of construction material or fabrication techniques and technologies to be used are made in the course of the design process and not beforehand.  

For those projects where this set-up is almost determined, the physical modelling material can be selected in a way that conceptually incorporates the known constraints and potentials of the latter stages of design into the early exploration: through the agency of material, constraints are conceptually incorporated in the exploration domain and are turned into design drivers. For instance, if construction materials are constrained to planar ones, the selection of planar modelling materials such as paper for manual modelling incorporates the constraint of the construction material into the exploration model. For projects that are open-ended and whose materialisation set-up is not determined, the designer’s attention to ways of working with a material and exploring its capacity can suggest new construction
strategies or materials to be developed. It can bring things to the designer’s mind that were not planned and thought out in advance. Because material is independent from the human mind and has its own properties and capacities, it can introduce unplanned things to the exploration.

By selecting certain materials and giving them roles, the designer turns the neutral space of exploration into one in which the intention is embedded but which also allows for the mind-independent behaviour of material. Through material selection it is possible to incorporate the constraints and potentials of the materialisation stage into the exploration model. Moreover, by virtue of its capacity and properties, which are mind-independent, the material used in the exploration can inform the designer’s initial intention and surprise her with new possibilities. Thus by conceptually incorporating aspects of materialisation into the exploration, material acts as a design driver.

When working with material in the exploration, scale is an important issue. Shifts in scale entail changes in materials, tools, and ways of making. Scalability is the ability to be enlarged and realised at different scales of material practice, from small-scale physical modelling to full-scale construction and vice versa, and can be found in different aspects of a project (e.g., formal, structural, constructional). Aspects of materialization that can be incorporated with or suggested by a physical modelling material at the early design stage are those that can be propagated to the model’s full-scale counterpart—those that are scalable.

On the one hand, by paying attention to material behaviour the designer can link the exploration to the affordances of construction; on the other hand, a material’s behaviour and its points of failure can push the boundaries of construction and impact the designer’s intention: paying attention to the inherent characteristics of a physical model that can be propagated to its full-scale counterpart may suggest new construction strategies for the latter. This can push the boundaries of existing construction materials, fabrication techniques, and fabrication technology, as well as existing modes of design.

The following section identifies a number of material characteristics that are connected to the issue of scale, both as drivers to link the exploration with the production context and in terms of their potential for enabling significant invention in the exploration.

Material format: scaling fabrication techniques

Material format is used here to refer to the external form in which a material is made available to the designer. It refers to the shape, size, and appearance of a material. Wood, for example, is available in the form of logs, panels, boards, and so on. The format of a material can suggest how to process it so that it can become part of the larger artefact. As Rob Thomas notes, “the material at any particular point in time is brought into existence through a developing chain of events, both ‘natural’ and cultural, and has the potential for a myriad of future interactions and transformations” (Thomas 2007, 6). A tree that is harvested from the forest goes through a processing chain before it is provided to us, during which it is shaped into formats such as dimensional lumber and plywood; this means that materials are prepared and put into a particular arrangement beforehand, and as a result come in certain dimensions, shapes, and formats and have predictable performance qualities. This is relevant to all classes of materials, from construction materials to modelling materials and from conventional materials to newly developed ones. Even materials used with new digital technologies, such as 3D-printing materials, are offered in formats relevant to their respective technologies (e.g., powder and plastic string are developed in relation to different 3D printing technologies).
The availability of material artefacts in certain formats, shapes, and dimensions and with different performance qualities has a deep and subtle relation to the material’s processing techniques and technologies. For instance, in the industrial revolution, the emergence of the industrial production of artefact wood and the concept of the wood stud, which led to a “mass production structural element with predictable performance criteria,” was enabled by virtue of new methods for harvesting and milling wood—methods that enabled the “transformation of timber into lumber and the irrevocable passage of wood into a standardized, reproducible product” (Kennedy and Grunenberg 2001, 6). At another level, “the invention of the rotary cutter, the perfection of wood glues and synthetic resins and the development of engineered plywood sheets . . . created an inexpensive sheathing system for the wood stud construct” (Kennedy and Grunenberg 2001, 6).

Materials, as we use them in society, are cultural artefacts that have the potential to produce larger artefacts, such as buildings. This potential is closely related to the machining technologies and techniques that enable their transformation into buildings and other structures. The advances in CNC machining have enabled the realisation of geometrically complex buildings built from non-standard parts. The digital information embedded in CAD models can be translated into control data to directly drive the CNC machinery used to fabricate such parts (see Fig. 2.6 in Chapter 2). Kolarevic identifies the following four fabrication techniques related to digital fabrication tools commonly used to realise complex geometric objects (2003b, 34–38):

- two-dimensional cutting techniques;
- three- to five-dimensional subtractive techniques;
- forming techniques;
- and additive techniques.

Two-dimensional cutting techniques are used for flat materials, three- to five-dimensional subtractive techniques for sheet materials and blocks or volumes of material, forming techniques for flat and block material, and additive techniques for amorphous material.

The following descriptions of these techniques, adapted from Kolarevic, are presented in the author’s “Technological Advances in Design and Construction” (Aghaei Meibodi 2012b):

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92. What is interesting about the Lewis House project is that cloth as a design proposition for the building suggested and advocated a construction material other than the conventional ones in use at the time. As Shelden notes, Gehry and his design team “were looking for a construction material that would do that cloth-like things for a long time, and they just couldn’t find them . . . they had been looking at composite . . . i knew you could build with composite, but they couldn’t get the fireproofing certified” (Shelden 2014a). As a result, the designers post-rationalised the digital surface in accordance with the fabrication and material affordances of the time so that it could be built from shingles. Twenty years later, it is actually possible to use cloth-like construction materials such as composites to produce the forms cloth assumes at the building scale. For instance, Bill Kreysler used composite in building the facade panels for the expansion of the San Francisco Museum of Modern Art.

93. Materials such as cloth, bubbles, and hanging chains also work in design exploration, even though they do not have the immediacy as working with digital fabrication tools, construction material, and techniques. But they enable immediacy between the form they assume and the forces that affect them. In this case the overall form a material assumes in relation to forces is scalable.


95. For a detailed description of these techniques and their implications in architecture, see Digital Design and Manufacturing: CAD/CAM Applications in Architecture and Design, by Daniel Schodek, Martin Bechthold, James Kimo Griggs, Kenneth Kao, Marco Steinberg, November 2004 (Schodek et al. 2004).
Cutting techniques
Cutting techniques are used in two-dimensional fabrication and involve the movement of the cutting tool on two axes in relation to the workpiece, for example a sheet of material. Technologies such as laser cutting and electronic discharge machining (EDM) are based on the use of thermal energy to cut—melting or burning the material in order to cut it. Technologies for smoother cutting, such as water-jet cutting, punching and blanking, die cutting, and glass scoring are mechanical techniques and it is erosion that cuts the material. Rarely used in architecture, photochemical machining is a chemical cutting technique.

Subtractive techniques
Subtractive techniques are used in three-dimensional fabrication and involve the removal of material from a solid block. These techniques use a variety of chemical, thermal, and mechanical technologies.

The technology most commonly used in architecture is the CNC milling router, which is a mechanical technology. It uses a combination of drilling and grinding to remove material. The milling machine is axially constrained; milling a solid on three axes is an extension of two-dimensional cutting with the added ability to move in the Z direction. The range of shapes that can be produced by this type of machine is limited, as it cannot produce undercuts (Fig. 4.3). For those shapes requiring undercutting, a four- or five-axis milling machine is used. The CNC milling machine has been widely used in architecture. The best example is the Walt Disney Concert Hall in Los Angeles, whose geometrically double-curved stone panels were CNC milled in Italy and then shipped to Los Angeles to be assembled on a steel frame at the site.

Forming techniques
Forming techniques shape material by deformation or reshaping using mechanical forces, heat or steam, moulding the material in order to achieve the desired form. Such machines can perform steam bending, simple wood lamination, composite wood lamination, or shape molten glass and plastics, depending on the material that is being shaped. A comprehensive study of the technologies used in forming has been presented by Rob Thompson in Manufacturing Processes for Design Professionals (Thompson 2007, 22–232).

Additive techniques
Additive fabrication is the forming of an object by adding material layer by layer. It is referred to as solid freeform fabrication, layer-by-layer manufacturing, and rapid prototyping. The methods used for this technique are based on light, heat, or chemical reactions, and the many different technologies that exist for additive fabrication include stereolithography (SLA), selective laser sintering (SLS), 3D printing (3DP), fused deposition modelling (FDM), and multi-jet manufacture (MJM). However, due to the expensive equipment, time-consuming production, and limitations on the size of the objects that can be produced, this technique has limited applications in the field of building design and manufacture. However, a relatively new
additive technology called Contour Crafting, which allows rapid layer-by-layer pouring of concrete for use in full-scale building projects, has been invented and patented by Behrokh Khoshnevis of the University of Southern California.

Casting techniques
Casting techniques are used for forming amorphous materials such as concrete into a particular shape. This technique involves a great deal of formwork development and is investigated in Experiment 3 in this dissertation.

By selecting a material format one can incorporate the constraints imposed by fabrication techniques and technologies into the early exploration and make them an inherent part of the exploration model. By selecting the material format with respect to fabrication techniques and technologies or vice versa, the designer can scale up the fabrication method from small-scale to large-scale models and then to full-scale construction. For instance, in Experiment 2, Strip, the selection of paper strips as modelling material constrained the exploration to forms that could be fabricated from sheet material; the designers explored alternative forms whose constructability was ensured.\textsuperscript{96} Shifting from flat paper to MDF and finally to plywood, the designers continued to employ two-dimensional cutting techniques.

We may use the confluence of material formats and the fabrication techniques afforded by CNC machinery to identify classes of physical modelling materials:

- sheet, flat, or planar materials: e.g., paper, MDF panels, Masonite panels, plywood sheets;
- volumetric or block materials: e.g., wood planks, foam blocks;
- amorphous and liquid materials: e.g., gypsum, concrete.

Material behaviour: scaling form and structure
Incorporating the fabrication constraints for a given material format into the exploration does not necessarily endow the exploration with other aspects of materialisation, such as construction methods or structural concerns. Besides the format, which determines how a material can be processed, there is also material behaviour—what a material does when it faces an event. For instance, when rotated in opposite directions from its two ends, a strip of paper twists. Two kinds of material behaviour, formal and structural, are used in this research to examine the potential and challenges that material behaviour brings into the exploration across the scales of material practice.

Formal similarity
There are materials that have similar formal behaviour when faced with events (behavioural options), meaning that they are capable of assuming or suggesting similar forms. For instance, strips of paper and balsa wood both twist and assume a similar shape when rotated in opposite directions from their two ends. By considering formal similarities or correspondences between different materials, the designer can scale the form from small-scale to large-scale physical models.

The selection of the modelling material for every physical model throughout the process may be made with a mind to its capacity to take on certain forms. In physically exploring

\textsuperscript{96} In addition, Shelden’s dissertation presents a number of Gehry’s projects in which the selection of the paper strip as a modelling material was made with intention of constructing the built forms from sheet material (Shelden 2002, 110–119).
curvilinear forms, for example, the designer may choose any material that can take on curvilinear shapes and is easy to manipulate by hand and then, based on formal analogy, search for a construction material that can take on similar forms.\footnote{97} This is observable in Experiment 2, Strip. While attention to formal analogies between materials at different scales allows the designer to scale the form from a small-scale physical model to a larger one, it does not determine its construction method. That is, while working with material that has similar formal behaviour allows the designer to scale up, or propagate form across different scales of physical models, the construction method must be adapted for each scale. As scale increases, the materials with which the physical models are made are more rigid than their smaller-scale counterparts and require more sophisticated construction methods. A strip of paper is continuous and easily manipulated, whereas for a full-scale counterpart in a construction material such as wood to assume the forms suggested by a paper strip, more sophisticated construction methods are required, such as the lamination of sheets in segments to be assembled (Fig. 4.4).\footnote{98}

**Structural similarity**

Materials that are capable of assuming similar forms do not necessarily have similar structural behaviour, and may not perform structurally in the same way. In this context, *structural behaviour* speaks of the force paths when a material is subject to forces, of its construction, and of ways of treating the material in a larger system with respect to other construction elements—material is treated as part of a larger system rather than as a standalone component. In the image below, the network of strings and the network of wooden dowels both assume the geometry of a line (Fig. 4.5). They both assume or project a network of lines. However, while the choice of cable puts the system in tension, the choice of wooden dowels puts the system in compression. The attention to structural behaviour is a shift from conceiving of a material as a standalone artefact to seeing it as a component within a spatial assemblage and understanding its behaviour and load paths within in a larger system.

The selection of physical modelling materials with respect to their structural behaviour and load paths can endow the exploration with information about construction and assembly. It incorporates knowledge of the material arrangements, assembly, and construction of the intended building into the exploration, extending the domain of exploration towards material composition and the arrangement of components. Tensioning a wire and binding wooden dowels require two different construction set-ups, which can dramatically impact the direction of design. Materials with similar structural behaviours imply similar methods of construction and assembly—both strings and tensile wires have to be tensioned at both ends in an assembly because their structural behaviours are similar. Therefore, when using string in the exploration and wire in the built form, the designer can scale up the assembly methods when moving from one scale of making to another.

Material is not a neutral agent waiting for the designer to encode its capacity; rather, by virtue of its properties and capacities, material charges
the domain of exploration, driving the exploration and impacting the designer’s intention. In Experiment 4, Hyperboloid of One Sheet, the designers’ intention was to materialize the geometric form of the hyperbolic paraboloid. Once explored with different materials, the character of the materials and their behaviour impacted the designers’ intention and guided them to proceed with the design exploration.

Considering the convergence of a material’s format, formal behaviour, and structural behaviour, one can place the previously classified material types along a spectrum with flexible (those materials that can easily be deformed) at one end and rigid (those that require sophisticated techniques for deformation) at the other.99

Material format versus material behaviour: shifting scale

Two materials with the same format do not necessarily have the same properties, and may not assume the same form when forces are applied. Therefore they do not have the same capacities, and will not necessarily have the same response to an event such as being pushed, folded, or twisted. For example, paper and Masonite are both sheet materials amenable to two-dimensional cutting techniques, but when folded, paper bends while Masonite breaks. A paper strip can easily assume a V shape when folded by hand (Fig. 4.6).

As discussed above, in the design process physical models tend to increase progressively in both scale and detail (Porter and Neale 2000, 19). The move from small-scale to large-scale models requires changes in material as well, and changes in material as a result of scale shifts mean changes in the way of making and manipulating the material. As the physical models are scaled up, certain things do not work the same way and gaps are created. In these gaps between models and scales there is substantial space for innovation. In the example of folding paper, if the designer wishes to propagate the V form assumed by the paper to the full-scale counterpart, and at the same time is intent on using Masonite in the larger-scale prototypes—perhaps due to constraints imposed by the fabrication tools available—there will be a tension between what Masonite can do and the designer’s intention. Here, Masonite’s inability to be folded into a V shape would push the designer to investigate solutions such as joints to enable the construction of the form with Masonite (Fig. 4.7).

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97. Similar, not exact. No two materials, even of the same kind, will assume exactly the same shape unless they are forced to. Two pieces of paper the same size do not assume the same geometry of twist.

98. Based presumably on sheet size availability and its tie in to manufacturing of sheet materials.

99. In engineering terms this would concern the shear property of material. However, the author intentionally avoids this technical term here in order to emphasise the degree of freedom a modelling material has to take a form and allow the designer to shape it.
Even materials that are formally or structurally analogous do not necessarily carry out specific tasks in the same way when shifting scale. In the example of shifting from a small-scale to a large-scale physical model and replacing a paper strip with a strip of balsa wood, both can perform the task of twisting—they have a formal analogy—but a wooden strip twists less than a paper strip when the same amount of force is applied. Moreover, while both a wooden strip and a paper strip bend when they are pushed from both ends, they do not perform the task of assuming a curvature to the same degree: paper can be bent to a greater degree than balsa wood. This gap in the degree of performance between different materials that the designer encounters when changing scales can become a space for the invention and introduction of new design elements. Questions about how much a material can be bent or twist point towards the degree of the material’s performance. Material performance is a measure of a material’s ability to carry out specific tasks, such as twisting (degree of twist). Materials with the same format do not necessarily have the same behaviour and performance following an event, and materials that are formally or structurally analogous do not necessarily perform the same task to the same degree.

Usually construction materials are not as easily manipulated by hand as modelling materials are, so the shift from physical model to large-scale prototype to built form may require more a sophisticated way of processing material to achieve the shape that was initially suggested in early physical modelling. A paper strip can easily assume different curvatures, while a wood strip has to go through lamination to assume the same shape. Lamination as a way of construction introduces new elements to design, for example the number of layers of lamination and length of the laminated piece. This approach would then require the designer to specify the behaviour of the construction material rather than simply select it from an existing range.

Significant findings and invention do not occur immediately. Through persistent physical modelling and scaling up, the designer brings new construction knowledge into the design process with each new physical model by challenging the capacity of the construction material. In Experiment 1, Honeycomb, for instance, to achieve the same shape when moving from paper to cardboard and from cardboard to MDF, decisions about construction were made. Achieving folds with cardboard required processing the material; the creation of the fold was the result of the fabrication process and the material’s properties. Laser-cutting a cardboard strip halfway through was combined with cardboard’s properties, allowing the material to assume the fold shape. MDF required the invention of joints to create a fold at the same angle (Fig. 4.7).

4.2. Geometry as a medium for design

In contrast to material, which is mind-independent, geometry is mind-dependent. Being mind-dependent doesn’t mean that it is not related to the material world—some geometric concepts may have been invented to describe the logical relationships inherent in material and material-world
phenomena, while some others may have been invented as a result of imagination of the human mind alone. To distinguish these two views of geometry, Einstein suggested that the first be called “practical geometry” and the second “purely axiomatic geometry” (Einstein 1923, 32). The first category suggests that geometry’s “affirmations rest essentially on induction from experience, but not on logical inferences only,” the second that “the matter of which geometry treats is first defined by the axioms,” which “are free creations of the human mind” (Einstein 1923, 30).

Whether practical or purely axiomatic, though, geometry exists as a result of a long process of reasoning and is always meaningful as part of a mind-dependent system. In *Grundlagen der Geometrie*, David Hilbert argues that geometric objects—point, line, and so on—only make sense as part of a system, such as the Euclidian system, and not outside of the system (Hilbert 1899).

Whether geometric concepts and their associated systems are seen as solutions to some rational equation or as solutions to the physical and material world, they are not usually found by the designer but rather are utilised and applied in the design process to aid the designer in achieving a goal. For example, in the case of Frank Gehry’s unbuilt Lewis House project for Peter B. Lewis, the geometries, spline surface, and curves are used as mediums first for the designer to digitally and geometrically represent the waxed velvet physical model (Fig. 4.8), and second to provide the designer with a design domain in which to proceed towards the rationalisation of form in order for it to be built from planar parts.

The images to the left (Fig. 4.8) show a waxed velvet model created by shaping draperies to communicate the designer’s intention—the formal aspects of the design. Initially, the form of the waxed velvet model was represented digitally and geometrically as point clouds by scanning its outermost surface using a digitizing arm. However, the point clouds were not sufficient to enable the computational experts to realise Gehry’s formal intention to proceed towards the realisation of the project. The further reconstruction of the form in CATIA software as a digital spline surface, which is a flexible surface, was done with the intention of rationalising the form in order for it to be constructed from planar materials. Using the digital spline surface,
the form was then post-rationalised to be built from shingles—sheet goods—using two-axis digital fabrication tools. The materialisation of the form is the Horse-Head Conference Room at the bottom of the image, which was built as an exploratory prototype for the Lewis House.

In this example, the perfect and accurate digital spline surface is a visible figure of a tangible object, the wax velvet model. The physical and digital models entail two disparate sets of mediums for design, material and geometry, which are essentially different. Generally speaking, when going through the process of drawing or digitally modelling geometry, the designer or computational expert tends to forget that the “visible figure presented to his eye is only the representative of a tangible figure which is what he is really attending to; it doesn’t occur to him that these two figures have really different properties, and that what he demonstrates to be true of the one is not true of the other” (Reid 1785, 66).

Geometric concepts such as surface may be seen as superficial as opposed to artefactual and material things. *Superficial* in this context means materially deficient and general, and is in contrast with the actual object, which is materially significant. In the given example, when scanning the wax velvet model and representing it through digital spline surfaces, the *surface concept* is used only to simulate the positions of the most exposed layer of the physical model, and does not automatically provide the designer with the thickness, hardness, or any other properties of the fabric material. Various cloths respond differently to the designer’s acts of manipulation, as a result of the raw material they are made from and how they are manufactured. A digital surface, however, has a general behaviour unless it is constrained numerically to designate and simulate a particular kind of fabric.

While a cloth is specific and particular by its nature, the digital spline surface is general. On the one hand, the notion of generality makes geometry a useful medium for design, as it can be used to represent a large domain of materials. For instance, the surface concept can represent both a sheet of fabric and a sheet of paper. On the other hand, unless they are constrained prior to use these geometric concepts, as they are available to the designer through CAD, are liable to exceed the capability of the construction material, capability of fabrication tools, or logic of construction. For instance, if the designer intends to use two-axis fabrication tools to fabricate the final product, initiating the design exploration using a cloth or digital freeform surface changes how the designer explores with them and proceeds with design. A piece of cloth can be spread on a table so that it can be laser cut using two-axis cutting techniques. When exploring by means of a cloth, the designer is always assured that any form the cloth assumes can be unrolled back onto a plane. The form assumed by the cloth can be scaled up for large-scale prototypes using a 3D scanner and digital surface as representation medium, assuring the designer that the form assumed by the digital surface can be unrolled onto a plane—as it is the exact form assumed by the cloth. The rationalisation of the surface from planar elements is assured. Meanwhile, when initiating the exploration with a digital flexible surface, the designer may stretch the digital surface in a way that intersects or intertwines with itself or is formed in a way that cannot be unrolled onto a plane and would thus exceed the capability of fabrication—in other words, it can exceed planarity.

In the context of architecture as material practice, where material and empirical experimentation play important roles and design deals with real-world problems and tangible objects, the designer must strip the geometry of its merely formal or logical character by coordinating it with real objects of experience. This means linking geometry to material and material-world problems.
4.2.1. Geometric representation of materiality

Geometry takes on different roles at different points in the design process, and it is the designer who, with active choice, identifies the role of the geometric concept throughout the design process. By taking on different roles, geometry can link the exploration domain to the material world. In the experiments conducted in this dissertation, one can perceive the changing role of geometry throughout a project and the different roles that are given to geometric concepts from one project to another, for instance as representational tools, descriptive tools, translation steps, or seeds for design ideas.

One of the roles geometry plays is that of a representational tool. Through its representational capacity, geometry can incorporate aspects of materiality, linking the exploration with materiality. In other words, by considering the representational capacity of certain geometric concepts, the designer can incorporate materiality into the descriptive domain of exploration and link the formal logic of a geometric concept to the characteristics of a material. In doing so, the designer must formulate and abstract real-world problems and find suitable geometric representations for them. Geometry and material have significantly different properties: indeed, geometry as a medium for design is matterless. In architecture as a material practice, where material and real-world problems play a central role, geometry must coordinate the real, tangible objects of experience. This section examines the capacity of geometric concepts to incorporate aspects of materiality into the exploration and to represent material and real-world problems in the exploration by means of formal logic.

In a discussion of the Lewis House project, Dennis Shelden notes that “we have these cognitive models, such as surface, and we have certain physical world problems for which we look for representation that fits. The surface happened to be a good solution to represent cloth” (Shelden 2014a). In this example, the cloth is certainly not the surface, nor is the surface the cloth. The two exist independently of one another: the cloth in the physical world independent of our minds, and the surface as a geometric concept independent of the physical world. The capacity of the geometric concept to represent materiality enables

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102. “When a geometrician draws a diagram with the most perfect accuracy, and keeps his eye fixed on it while he goes through a long process of reasoning and demonstrates the relations of the different parts of his figure, it doesn’t occur to him that the visible figure presented to his eye is only the representative of a tangible figure which is what he is really attending to; it doesn’t occur to him that these two figures have really different properties, and that what he demonstrates to be true of the one is not true of the other” (Reid 1785, 66).

103. Raw materials, such as naturally and artificially generated material or a blend of both, and various constructions such as woven, non-woven, knitted, netting, or technical fabrics (e.g., Gore-Tex). No two fabrics will assume exactly the same curvature when folded by hand.

104. The following is the author’s interview with Dennis Shelden on the interdependencies that exist between the geometric concept as a design problem, materiality, and material-world problems. Author: “Dennis, do you think cognitive models like the developable surface and the sphere were developed as solutions to physical-world problems?” Shelden: “If you ask a mathematician to describe a developable surface, there are bunch of things they would say, but they wind up being behaviour that we could say, ‘what a coincidence, I was looking for a model for paper, which is a developable surface. To some order of approximation, paper does the same thing as the desired features of these developable-surface geometric algorithms, so I will use that one.’ It is not that the developable surfaces are the digital representation of the physical paper. We have these algorithms and we have these physical-world problems and we look for representation that fits.” Author: “So can we say that there are many algorithms out there that are not necessarily extracted to model the physical world and are the product of the cognitive mind, which could be used in design?” Shelden: “Yes.” Author: “So, as the material world helps us to come up with design solutions and design ideas, geometric invention has been playing an important role in explaining material problems, aiding designers in ideas that lead to new materiality.” Shelden: “Yes, I think it you are right.”
the designer to create links between the theoretical domain of exploration and the empirical domain of exploration in the material world.

Design exploration in the context of architecture as material practice entails working with material and making in the course of design, as well as considering in the early stages of design aspects of materialisation that belong to the latter stages. This means being concerned with such things as economical realisation, the affordance of fabrication methods, building material capacities, methods of assembly and construction, a structure’s stability against gravity, wind, snow, and so on. Certain geometric concepts can be used to incorporate these aspects of materiality into the exploration and give the designer access to them by means of formal logic. In open-ended projects, geometry’s formal logic and representational characteristics can also suggest construction materials and ways of making. This is demonstrated in Experiment 4 in Chapter 6.

To explore the capacity of geometric concepts and their associated systems to support form exploration with reference to materiality—material capacity, fabrication capabilities, and construction logics—this research employs classes of surfaces and curves as mediums to represent the outer layers of tangible objects and empirical aspects of materialisation. In doing so it investigates the agency of geometry in incorporating aspects of materiality into exploration. To explore how material constraints can be incorporated into the exploration model through geometry, the experiments in Chapter 6 seek to correlate material and geometry in curved and surface-based forms.

One can roughly describe a curve as a one-dimensional series of points, and a surface as a type of two-dimensional skin that can be generated through its profile curves (Fig. 4.9). Curves and curved surfaces are convenient means for creating a surface-based geometric model. The ability to easily control B-spline and NURBS curves and surfaces makes them excellent tools for computer-aided geometric modelling. In the last thirty years, many projects have proven the formal representational capabilities of surfaces and curves for a tangible object. The following are the classes of surfaces used in the experiments conducted in this research.

**Planar surfaces: incorporating sheet materials**

Planar surfaces are two-dimensional and can take any shape in a two-dimensional plane. These surfaces are the most constrained type to model with, as they cannot move beyond the two-dimensional plane. However, they are frequently utilised in the rationalisation of freeform surfaces (Fig. 4.10). They are found to be a good representation for building components that are essentially two-dimensional, such as CNC-cut plate elements. The two-dimensional boundary curve of a planar surface can be easily fed into CNC fabrication technology for the manufacture of building parts.

In this study, planar surfaces are used to formally represent building elements that are made of flat, rigid construction materials and are found to be a suitable geometric medium for doing so. For small-scale modelling, flat physical modelling materials such as cardboard can be used to materi-
alise the shapes of planar surfaces. Usually planar surfaces are used to rationalise complex forms due to the affordance of the fabrication methods associated with them and the economic benefits of using flat material. In Experiment 1, the use of a planar surface enabled the rationalisation of freeform surfaces as well as the economical production of the form from planar material.

Freeform surfaces: incorporating forces and fabrication techniques
In contrast to planar surfaces, so-called freeform surfaces are the most flexible surfaces for creating a computational 3D geometric model. Their use in architectural design has been associated with form-finding techniques and a number of fabrication techniques afforded by CNC machinery. In Experiment 1, the use of freeform surfaces gave the designers a means to conceptually integrate forces (gravity and wind) into the exploration, as well as to investigate and incorporate fabrication alternatives.

Many industries have found the concept of surface useful. In the aerodynamics industry, surfaces are used to represent the outer layers of physical objects so that engineers can simulate wind behaviour around airplanes. The initial development of digital surfaces, however, sought to do more than represent the outer layer of an existing physical object: they were developed in a way that could communicate with CNC machinery to enable the production of new objects. Indeed, the development of freeform geometry in mathematical description was initiated by the aeronautics and auto industries in the 1940s and 1950s out of their need to store a surface design digitally and communicate it to a numerically controlled (NC) milling machines (Pottmann et al. 2007, 364).

In Experiment 1, digital freeform surfaces were found to be useful, as they are capable of mediating between the two stages of conception and production. While freeform surfaces are flexible enough to allow changes to their overall form in response to forces, they also allow the designer to embed fabrication principles that enable designers to slice them up in ways that can be fabricated using CNC machinery (Fig. 4.11). Geometric constructability systems (e.g., panelising, slicing, egg-crating) are found according to the affordance of digital fabrication tools—and indeed, this is the reason for the rapid utilisation of digital freeform surfaces in architectural design in general over the last twenty years.

105. Modelling geometries, as opposed to modelling material, with the aid of computer power. Clearly this is dependent on the affordance of the computer-aided design tool that is chosen for computer-aided geometric modelling. For example, whereas Rhino affords working with freeform surfaces, the early ArchiCAD software did not.

106. As much as the material world helps us to explain mathematics, mathematics and geometry have played an important role in explaining the material world.

107. Or, one could say that the freeform surface has the capacity to enable designers to embed CNC machining techniques into the exploration space.
The use of freeform surfaces in design usually entails rationalisation. Rationalisation in this context is understood as the resolution of rules of constructability into project geometry (Shelden 2002, 78). "The aspect of the design process that is concerned with making irregular shapes buildable by efficient means is referred to as geometry rationalisation" (Fischer 2007, 589). Geometric rationalisation connects the geometric form to the construction material, fabrication, construction, and assembly logics. Geometric rationalisation is the process of making complex forms more constructible, more rational for construction. In most of Gehry’s projects there is an attempt to rationalise a digital surface so that it can be constructed from sheet construction materials. As Shelden notes, “many of the efficiencies in building systems used on Gehry projects are derived from building components that are essentially two dimensional. CNC cut plate elements, flattenable surface elements…” (Shelden 2002, 64).

In the Experiment 1, the choice of a digital freeform surface provided the designers with design domains that were able to incorporate fabrication techniques and forces into the exploration domain. Its use therefore gave the designers the ability to mediate between a curved whole form and its parts, which could be fabricated from sheet material.
Developable surfaces: incorporating two ways of making

In contrast to the freeform surface, which needs to be rationalised in order to be fabricated from sheet material, the developable surface embeds a fabrication rationale. Developable surfaces are special forms of ruled surfaces that can be unfolded into a plane without distortion such as tearing apart or compressing (Lang and Röschel 1992, 291). While ruled surfaces can be double- or single-curved, the developable surface has only a single curve. For this reason they are also known as single-curved surfaces.

In architecture they are commonly used with reference to the constructability of curved forms from sheet material. Since these surfaces can be unfolded into a plane without deformation, they can easily be materialised by bending a flat sheet of material such as paper, sheet metal, cardboard, or plywood (Fig. 4.12). As a result they have found applications in various industries, such as forming ship hulls, shoes, automobiles, clothing, and complex building envelopes. One common use of this class of surface is for the rationalisation of complex freeform surfaces. Some of Gehry's projects, for example, used developable surfaces as a tool to rationalise freeform NURBS surfaces: in this case the complex freeform is rationalised to a number of developable surfaces that can be then unrolled into a plane and fabricated from sheet-material components (Shelden 2002, 101–155).

In this dissertation, however, developable surfaces are not used as secondary surfaces to aid in the rationalisation of a freeform surface. Rather, they are used as a common ground—a common language—to associate two scales of material practice: small-scale and full-scale ways of making. While flat and flexible sheet materials such as paper can assume complex curved forms that are geometrically developable, the assumption of these forms by building materials such as plywood (i.e., rigid materials) entails more sophisticated forming techniques such as lamination.

108. Shelden’s dissertation, in which he explores various representations for surface constructability, demonstrates the efforts to rationalise digital surfaces so that they could be constructed for Gehry’s curvilinear building projects. See Shelden, “Digital Surface Representation and the Constructibility of Gehry’s Architecture,” PhD thesis, Massachusetts Institute of Technology, 97–130.

109. Here surface is a design instrument.


111. For example, hyperbolic paraboloid and hyperboloid surfaces are double-curved ruled surfaces, thus not developable.
In Experiment 2, Strip, the developable surface enabled the designers to explore methods of deforming of paper strips in accordance with the method of moulding that belonged to a later stage (Fig. 4.13). It mediated between two ways of making, namely twisting by hand and lamination with the aid of a mould. The developable surface represented the paper strip digitally in terms of its parameters and geometry, and linked it to fabrication and construction constraints such as the size of the machining bed, which defined the maximum dimensions of the material to be cut. Moreover, the surface enabled the design team to explore methods of constructing the moulds used to materialise the curved form, originally assumed by paper, with the construction material. It linked the form assumed by paper in the early exploration with the form afforded by the construction material. It ensured the fabrication of a curved form from planar material with a concern for the method of forming the sheet construction material, material fabrication, economy, and methods of forming.

Hyperbolic paraboloid and hyperboloid of one sheet: incorporating structural stability and the linear character of a material

The hyperbolic paraboloid and hyperboloid of one-sheet surfaces (Fig. 4.14) are well known and established in architecture for their structural advantages, due to the forms of their curvatures. In contrast to single-ruled surfaces, double-ruled surfaces cannot be unrolled onto a planar surface without creasing, tearing, or stretching, and therefore they are not developable. Being double-ruled means that through every point of $S$ there are two straight lines that lie on $S$. “Through every arbitrary point $x$ of a double ruled surface two different generators $g_x$ and $h_x$ can be drawn. These rulings $g_x$ and $h_x$ define the tangent plane in the point $x$” (Pottmann et al. 2007, 318).

Hyperbolic paraboloid surface

In contrast to developable surfaces, which are single-ruled, a hyperbolic paraboloid is a double-ruled surface that assumes the form of a saddle (Burry 2011, 85). “A hyperbolic paraboloid is an infinite surface in three dimensions with hyperbolic and parabolic cross-sections” (Demaine, Demaine, and Lubiw 2014). Its vertical cross-sections are parabolas, while its horizontal cross-sections are hyperbolas. It can be created by reflecting a parabola about its vertex tangent and translating the rotated copy along the original one (Pottmann et al. 2007, 310).

Because of their linear character, combined with the saddle form, hyperbolic paraboloid surfaces have been found useful in designing and constructing stable thin-shell structures. Their linear properties enable them to be materialised from straight sections of conventional construction materials, such as lumber and steel, and their positive static properties allow the construction of shells with large spans and relatively small thicknesses. This type of surface is employed in Experiment 3 to enable the designers to explore the linear characteristics of a physical modelling material in relation to the constraints of two-axis CNC fabrication machines.

Hyperboloid of one-sheet surfaces

Similarly, the one-sheet rational hyperboloid is a double-ruled surface; it is a rotational surface resulting from a hyperbola being rotated about one of
its axes of symmetry (Beckh 2015, 24). Because of its linear character, combined with its overall shape, it is useful for designing tall structures such as towers. It has opposed double curvature and is curved inward rather than outward, which makes it very stable against external forces (Reid 1984, 34). This surface was employed in Experiment 4 to give the designers access to an assembly logic with reference to the constraints of the construction material.

Curves: straight lines, planar curves, and spatial curves

With respect to real-world experiments, curves have a variety of applications. Curves are commonly used as representations of CNC machines’ and robots’ tool paths. They can also be used to represent vector forces for robotic arms to bend or twist something. This research uses three types of curves: straight lines, planar curves, and spatial curves.\footnote{113}

A straight line is a special type of curve. It can be extended at its two ends infinitely, and it admits more than one Euclidean plane, that is, it lies in more than one plane. A straight line is a useful geometric representation for materials such as straight beams or tensioned wires. An array of a straight lines along a curve can generate a surface, which can stand in as the outer layer of an object whose parts are made using straight construction material such as lumber. Planar curves are those curves in a two-dimensional Euclidian plane that cannot admit more than one plane into themselves. Spatial curves exist in three dimensions; in contrast to the other two types, they cannot lie in any two-dimensional plane. An example of a spatial curve is a skew curve. These types of curves are used in all of the experiments in Chapter 6.

4.2.2. Ways of working with geometry in design exploration

In relation to the designer’s mode of operation, this dissertation identifies three ways of working with geometry in design exploration: manual mouse-based manipulation, descriptive algorithm, and the conceptual use of geometry outside of the digital domain. While these three ways of working with geometry are presented separately, in a design exploration the designer may employ them in unison.

Manual mouse-based manipulation

Mouse-based manual manipulation of digital instants, such as control points on NURBS curves or NURBS-based surfaces, is one way of working with geometry using CAD software. This is a relatively intuitive (sensual) way of operation. Despite the fact that “the mathematical concept and software implementation of NURBS as surfaces is a product of applied numerical computation” (Terzidis 2006, xii), the manipulation of them using the mouse is not computation (Terzidis 2006, xii) and does not entail an act of mathematical and algorithmic operation by the designer. The designer

\footnote{112} The geometric form is a result of the negotiation between two scales of making.

\footnote{113} For a mathematical approach to describing these lines, see Helmut Pottmann, Andreas Asperl, Michael Hofer, and Axel Kilian, Architectural Geometry (Pennsylvania: Bentley Institute Press, 2007), 217–230.
rearranges the control points to create a 3D model, deform it, and create an effect: the designer is in a semi-direct and relatively intuitive relation with the geometric construct of the 3D model. John Conway notes that the “three-dimensional mental images are connected with your visual sense, but they are also connected with your sense of place and motion. In forming an image, it often helps to imagine moving around it, or tracing it out with your hands” (Conway et al. 2010, 15). Following this description, the ability that mouse-based modelling allows designers to rotate the 3D model and manipulate it with the mouse can be considered intuitive, as it connects with our senses of place and motion. Moreover, since the designer is dealing with a geometric construct directly, the designer’s mode of operation relies on visual intuition. There is an immediacy between the designer and the geometric construct, meaning that the exploration of geometric form is not delayed by mathematical, algorithmic, or other operational modes. The mathematical and algorithmic calculation of the geometric model is not carried out by the designer, but by the computer. When dealing with geometry directly without necessarily entering into the details connected with a strict definition of it (such as the formula behind a NURBS surface) and the actual calculations, the designer benefits from visual intuition (Hilbert and Cohn-Vossen 1952, iii). This mode of operation is offered by 3D modelling software packages, including Maya, Rhino, 3D Max, and others.

Descriptive algorithm to generate geometric form

Descriptive algorithms can be used to generate digital geometric instances (such as NURBS-based surfaces) and 3D visualizations of ideas by describing the logical relations behind them. For instance, a point as a geometric object is defined by explicitly describing its axiom in terms of algorithm. This mode tends towards strategic and systematic abstraction: to either seek or define logical relations inherent in a maze of pre-existing geometric concepts. Here, the mode of operation shifts from the intuitive to the intellectual and requires preformalising the way that the geometric concept is to be generated using the algorithm—for example, how to generate a planar surface from four curves that stand in for its sides, or from four points that stand in for its corners.

Creating an algorithm to generate a geometric concept, and consequently a geometric construct, requires some degree of formalisation prior to the act of the actual designing. When working with parametric-associative systems embedded in the algorithmic system, the designer needs to plan ahead, prior to the act of design, to define which major elements should be dependent upon other elements, define the parameters of the model, and define the hierarchy of dependencies between the parametric geometries as well as the functions. Preformalisation and foresight are almost necessities. Therefore, the employment of algorithm in design requires the designer to perform logically.

Geometry used conceptually outside of the digital domain

While in general the use of geometry in the field of computational design is strongly connected to digital tools, it doesn’t have to be. Axel Kilian has remarked that “just because something is contained in the recorded digital domain as geometry, I would be curious if it is really that strictly enclosed conceptually.” In the Lewis House project, for example, the surface and curves are digital—communicated through the computer and CAD tools (CATIA)—but this does not have to be the case, and surface as a medium for exploration should not be conceptually restricted to the digital domain: it could just as well be in our mind, and be explored in synergy with material practice, without the mediation of a computer. In Experiment 3, geometry is used conceptually together with the material exploration. This experiment moves towards breaking out of categories and understanding geometry as a
concept and medium that aids the designer in proceeding conceptually in design. This is a conceptual use of geometry that goes beyond the immediate limitations of tools.

4.3. Interdependencies between the mediums of geometry and material

The designer is the one who, by active choice, creates the correlations and interdependencies between the disparate mediums of design, geometry, and material, and by doing so creates a meaningful exploration. The designer can find affinities and correspondences to create a correlation and interdependency between these mediums. Finding an affinity is a search for likeness: for instance, the likeness between a freeform surface and a cloth that assumes curvilinear forms. By finding affinities between mediums, their worlds overlap but do not necessarily correspond. The digital surface does not immediately correspond to cloth: as mentioned above, it behaves very differently than cloth unless it is constrained. Similarly, a line may have an affinity with wood, but not the same attributes and attitudes; for them to correspond to one another in a certain way, the designer may correlate them by creating a technical bond, for example by abstracting structural forces into the geometric model. To create correspondences the designer must match up the mediums of exploration. This matching can be done by means of technical bonds or through the designer’s evaluation of and interaction with the system.

If an affinity can be seen as a bond that is chosen between two mediums, one that is not forced by origin or technical necessity, then the designer is constantly creating correlations, actual bonds, between complementary mediums that are introduced through design. The designer can also create interdependent links between mediums that do not have affinities, by introducing another actor into the exploration or by acting as a mediator. In light of this statement, the designer’s knowledge of geometric concepts and the context of materiality play important roles in creating the exploration model. How do we find mathematical models and geometries such as surfaces to be useful tools in solving our real-world problems? How can we move beyond problem solving to exploring new opportunities? What are the ways by which the designer can create interdependencies between geometry and material that lead to significant findings not initially intended by the designer?

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114. In *Geometry and Imagination*, David Hilbert and Stefan Cohn-Vossen (Hilbert and Cohn-Vossen 1952) present the visual and intuitive aspects of geometry.

115. In the experiments conducted, this mode was employed throughout the design process. Sometimes the Grasshopper files are baked—the “bake geometry” option in Grasshopper takes the geometric result of the Grasshopper definition into Rhinoceros, so that the designer can directly manipulate the geometry using the mouse. However, a shortcoming of the software is that once the direct manipulation of geometry is over it is not possible to update its algorithmic definition in Grasshopper. In other words, by baking the geometry—which is a necessity for directly manipulating it—its connection to the algorithm and form description is cut off. Therefore, to proceed the design has to be abstracted through a new set of algorithms. A bidirectional relation would have been useful in the design process.

116. Axel Kilian, in a discussion between the author and Kilian in the final seminar event of this PhD, University of Toronto (Toronto, Canada), 4 June 2015.

117. Here the surface is projected through the computer screen. It is a digital surface, encoded in the computer, but it doesn’t have to be and could as well be in the mind.
4.4. Forming the design exploration through the mediums

Understanding the characteristics of material and geometry reveals two things that are significant to the larger subject of this research, which concerns design exploration. First, each of these mediums augments the exploration by facilitating different aspects of a project framework and they are not replaceable by the other. Second, interdependencies exist between geometry and material within the exploration. One of the important objectives of this dissertation in general and of the presentation of the experiments in Chapter 6 in particular is to show the interdependency that exists and that can be created between geometry, material, and algorithm in the exploration. What are the relations between geometry and the material world with respect to ideation and the designer’s intention?

If CNC machinery and computational geometry are used to shape the designer’s intention, which is the case in most of the computational design and fabrication projects done in the field, then the design exploration is goal oriented, and is bound by the constraints of the fabrication machinery. This approach can be seen in Experiment 1, Honeycomb, in which the design intentions are shaped by the capacity of CNC fabrication tools and by surface as a computational geometry that enables the incorporation of fabrication potential into the exploration domain. In this project, the geometry is made to conform to materiality and to the capacity of fabrication technology, and is even reconstructed and reformed constantly to meet the capacities of CNC fabrication tools. The use of material in the design exploration is also enforced geometrically, meaning that it is a result of a geometrically driven digital chain of design to fabrication. By measuring the geometrically enforced material and feeding the information back to the computational geometry, the computational geometric model is reformed. Here, the relation of computational geometry to enforced material geometry is that of geometric perfection to an imperfect material world. The geometry is made to conform to real-world problems, and the material is pushed to be as close as possible to geometric perfection.

If, on the contrary, the designer embraces material effects as part of the exploration and begins to engage with them as a design medium rather than as something that must be corrected, then the design mediums and the process will begin to inform the designer’s intention. This means that geometry is not treated as something that merely aids the designer in fulfilling the intent, and the relation between computational geometry and material in the world is no longer treated as that between perfect and imperfect or right and faulty. It also means that the role of digital fabrication machinery is not restricted to the mere execution of the geometric entities and algorithmic set-up of the designer’s intention. Instead, by creating meaningful interdependencies between different entities and mediums in an open-ended manner, the designer can sense and feed back the findings and treat the design exploration as a drifting design problem that constantly evolves and changes and may not end up where it started. Something interesting may emerge in the design process that was not expected or planned by the designer. In such an approach the design exploration is open-ended. This approach can be seen in Experiment 3, Hypar, in which the design team embraced material effects and played down the use of fabrication machinery as a pure execution of geometric entities at the very early stages of the exploration. By giving agency to the design mediums and treating the design exploration as a drifting design problem, new things emerged. By constantly sensing the new findings and altering them with the project framework, the exploration was pushed further and design intentions were reformed. In this project, the fold as a design invention emerged from creating an interdependency between paper and the hyperbolic paraboloid surface, and subsequently the folding of the paper was altered with the project framework of building a full-scale prototype out of concrete.
with a minimal budget, which led to the invention of the dynamic formwork and the concrete components as a secondary things as well as the casting of the hyperboloid of one-sheet structure, which gave birth to the fourth experiment.

In neither of the above approaches is the design exploration domain neutral: it contains the designer's intention through the selection of materials and geometries. When creating the exploration model, the designer embeds some of the intention in the material constructs and some in the digital constructs. The important difference is that in the latter approach, by leaving the exploration open in the early stages, the designer gives more agency to the design mediums and may end up somewhere other than was initially intended. By the way that these digital and physical entities are connected to one another, the designer can create a goal-oriented exploration or an open-ended one in which the designer's intention is informed by the process.

4.5. Reflections

In recent years there has been much discussion about computational design beyond geometry, in which geometry is not seen as central, and scripting data and algorithms are. However, geometry, paper, and other things one sees and touches—things that are visual and tactile—remain important. Geometry has a spatial character that makes the object of exploration visually communicable. The material and geometry used in the exploration models do not simply serve to represent the object, but rather are brought into alignment with, and stand in for, the material context of their full-scale counterparts, the capacity of their construction material, fabrication, and so on, and they are pushed to take on different roles throughout the design process. Material binds the designer and the exploration to its capacity, thereby keeping the exploration as close as possible to the real-word problem and affordances.

Materials have agency as design drivers by virtue of their inherent properties and capacities, while geometry has agency by virtue of its formal logic. Therefore, the incorporation of the material context by means of geometry entails the designer's abstraction of this context as logic, which can then communicate with logical form. The designer has significant agency. There are geometric and material mediums that can facilitate the designer's work, but at the same time it is the designer who gives different roles to geometry and material throughout the design process, and the designer who, through active choice, selects mediums and correlates one medium with another. Yet designers have to remain open to what the material has to say to them through their explorations. They have to be prepared to shift or adapt their design intentions in response to discoveries made at the juncture of materiality, algorithm, and geometry.
Chapter 5

The generative design exploration model
The previous chapters presented how the three mediums for design addressed in this research—algorithm, geometry, and material—can be used to enable form exploration with respect to the materiality of buildings and the challenges of materialisation. This chapter gives a theoretical description of the exploration model that is developed from the experiments. In the context of computer-aided computational design and the computer-controlled fabrication of architecture, I attempt to develop a theoretical description of the design exploration model that is both sufficiently flexible to allow creativity within the exploration domain and sufficiently specific to incorporate the potentials and constraints of the project framework (i.e., knowledge related to the materiality of the building: its materialisation, fabrication, construction, assembly, and cost).

This theoretical description of the exploration model is not a superficial one, but is developed based on the capacities of current digital design tools and the ways that algorithms, geometry, and materials can be explored by means of these tools as well as from actual practicing with them. The exploration model is constrained because the tools and other mediators that it comprises are not passive, but rather are limited in their affordances and prescriptive.

5.1. Mediating artefacts

Design exploration entails mediation. The act of exploration is to some extent a mediatory activity that involves developing models and their linkages by means of their affiliated mediums. In doing so, there are different kinds and classes of mediating artefacts that are closely linked to one another and influence how designers explore. The term mediating artefacts is used here in its general meaning, to refer to those things outside of and excluding the designer that intervene in the nonlinear and recursive cycle of the design-to-production process of the exploration domain — the comprehensive exploration model that encompasses them. These things vary from mediums for design—geometry, material and algorithm—to series of tools, to disparate sets of digital and physical models (constructs).

The kinds and classes of mediating artefacts involved in the writing process and the relations that exist between these mediating artefacts and the act of writing provides an analogy. In the writing process, the text in its key role as an instrument of semiotic mediation can be seen as a secondary artefact (Bussi, Mariotti, and Ferri 2005, 87) that mediates between the writer’s idea and the object of investigation, and physical tools such as the pencil, pen, and keyboard can be seen as the primary artefacts that mediate between cognition and semiotic artefacts. The primary and secondary artefacts are intimately linked to one another in a way that impacts how writers can explore them. If the pen is replaced with the keyboard or vice versa, not only are the relations between the primary and secondary mediating artefacts changed, but so is the way they can be explored by the writer. Primary and secondary artefacts are so intimately linked so that it is sometimes difficult to separate them.

Similarly, design exploration in the context of computational design and digital fabrication involves using mediating artefacts of various kinds and classes. Like the pen and the keyboard, the computer, CAD and CAE software, digital fabrication tools, disparate sets of digital and physical models, and the different mediums for design are mediating artefacts that are intimately linked to one another in a way that impacts how the designer can explore with them. For example, design exploration using a geometric concept such as surface as a medium for design through CAD is essentially different from using the mechanical tools of descriptive geometry to explore the same concept. While CAD allows the designer to work
with surface digitally and parametrically, the mechanical tools of descriptive geometry do
not. Indeed, the secondary and primary artefacts are sometimes developed with respect to
one another: the mechanical tools of descriptive geometry are intimately linked with the
nature of descriptive geometry and the way that they allow the designer to explore through
them by projection onto three planes.

Designers use these mediating artefacts as transitional objects to orient themselves in the
exploration domain. The mediating artefact is the key through which designers conceptu-
alis, develop, and produce architecture. The way a designer uses these mediating artefacts
can not only help to realise an intention, but also to design the intention and idea through-
out the process.

This research identifies a number of mediating artefacts that are used interdependently
with one another in the exploration model relevant to this research. While in the design
process these mediating artefacts work interdependently and in unison—and sometimes
one cannot work without another—they are named here to aid the reader in understanding
the elements of the exploration.

Mediums, based on their capacity: in this research I identify three mediums that can serve as
starting propositions for a design in the early stage and in which form can emerge and grow.
These mediums are algorithm, geometry, and material.119

Digital and physical models, based on developing formal, structural, and physical consider-
ations: models, including architectural models stemming from both modelling and model
making, can be seen as transitional artefacts. These are artefacts that on the one hand can
stand in for the designer, because the designer cannot state ideas without them, and on
other hand stand in for the designer’s intention of what to consider as part of the exploration.
The designer plays an important role in developing these models and setting the capacity
of each model. CAD, CAE expert, manual physical, and CNC-physical models are used in this
research.

Tools: hardware and affiliated software, machinery, and devices that mediate between the
designer and the object of design, and also mediate between disparate sets of models (phys-
ical and digital constructs). There are hardware devices with affiliated software that serve as
modelling tools (e.g., the computer for CAD or FEM) and hardware devices that serve as con-
duits or convertors from one model to another, as a channel for the transmission and con-
version of models (e.g., a 3D printer that outputs a physical model from a three-dimensional
digital model). This research utilises computers running CAD and CAE software, 3D scanners
(as input devices), and CNC machinery and robots (as output devices).120

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118. See also Michela Maschietto and Maria G. Bartolini Bussi, “Working with Artefacts: Gestures,
Drawings and Speech in the Construction of the Mathematical Meaning of the Visual Pyramid,” in

119. Capacity here refers to what the mediums are capable of offering to the space of exploration, in
this case mediums that can offer formal exploration.

120. Sensors are another kind of input device. They can be combined with output devices such as ro-
bots, which are usually positioned at the end of a process and used to execute a preformulated design.
Instead of treating the CNC machinery sector as a closed-loop system, the designer can add a sensor
to a machine in order to include the potential of feedback from the machine sector to other sectors.
This capacity to sense allows the machine to move beyond being merely an output device. This points
toward feedback-providing entities expanding beyond the human operator. Discussion between the
author and Axel Kilian in the final seminar event of this PhD, University of Toronto (Toronto, Canada),
4 June 2015.
By choosing mediums and tools and using them to create models, and subsequently defining the proportion of one model to another and creating links between them, designers address concerns and develop a concentration within the exploration model. We may conceive of the above-mentioned models as means for developing the capacity of concern. The designer’s concerns may be pragmatic ones, such as fabrication and manufacturing affordances (constraints and potentials), or non-pragmatic ones, such as consideration for the aesthetic articulation of form. The development of the capacity for concern by means of models is based on both the language that a model offers as a result of the tools and influential mediums from which it is produced and the subjective role of the designer. On the one hand, the designer models with certain concerns in mind and chooses constraints and potentials in creating a model; on the other hand, each kind of model the designer chooses to work with (e.g., a digital versus a physical model) has a language of its own and is prescriptive, and informs the designer’s mode of operation and intentions. The interplay between the designer’s intention and the character of the model impacts design ideation. Perez-Gomez notes that one of the misunderstandings that has been and still can be seen is conceiving of mediating artefacts merely as tools for reducing the building (a picture of building) or as a passive tool for merely representing the architectural design idea (Perez-Gomez 1982, 2). Whether they are design or representational tools, we miss seeing how these mediating artefacts themselves have agency in design.

While these models are presented above as distinct models, as opposed to speaking about a design model as a whole, it is important to point out that the exploration model encompasses all of these models and gradually emerges out of how these mediating artefacts integrate with each other. In the comprehensive exploration model, the individual models become less relevant, as does whether they are digital or physical. What is important is the way the mediums—algorithm, geometry, and material—are used and the roles they are given throughout the process. For instance, as can be observed in the experiments, in a particular case the role of geometry may be as a representation, as a translation step, as an originating idea, as an output of a generative algorithm, and so on.

5.2. The designer as creator and as mediator

The role of the designer throughout the process of exploration is changing. On the one hand, the designer sets up the entire exploration domain—the individual models and the links between them in the comprehensive exploration model. On the other hand, the designer becomes part of the model.

The designer creates the models and links them together, deciding for how long each model should be developed, where they have to be in relation to one another and for how long each model has to be in a given phase, and controlling the types of links between the models and the feedback rates. At the same time, the designer is defined as a part of the process and is deployed in it: in the exploration model, as a result of the way the designer uses algorithm in CAD, there is a certain degree of automation to the process that goes beyond the designer’s capacity. For instance, in those sectors of the process that entail computation, the design process is automated and carried out by the computer, while the designer becomes part of the productive apparatus, defining links and assigning directions of links between mediating artefacts, deciding how far back into the system something is fed, how often, and so on. The designer becomes another mediator between different sorts of mediating artefacts.
5.3. The exploration model

The various models created by the designer in the ideation and production of architecture, and the linkages between these models, are made possible through disparate tools and technologies (e.g., the computer, CNC fabrication machinery, computational technologies) and are influenced by different mediums ranging from materials to geometry to algorithms. The designer plays a significant role in this set-up, and the nature of the various mediating artefacts plays a significant role in how the designer explores with them.

Considering the confluence of the designer’s mode of operation and the means at the designer’s disposal, two main domains of exploration in which models are made can be considered: the empirical domain of the material world and the theoretical domain of the mind and the digital realm. The empirical domain encompasses both the hand and computer-controlled machinery in the process of making. The manual act of model making involves the hand directly, whereas with the use of automated, computer-controlled machinery the act of model making is mediated by the machine, but both stand in contrast to the theoretical domain in that they allow the designer to explore through experience rather than through theory or pure logic. These domains can work together in synergy, and each alters the designer’s mode of operation by virtue of the tools and mediums that can be embedded in it (Fig. 5.1).

The comprehensive exploration model emerges from linking the disparate models and sets of models made in these domains (Fig. 5.2). Each of these domains of articulation and expression has its own mediums, and each celebrates its own rules and regulations; consequently, the models associated with them entail a particular starting point for expression, ranging from the manual manipulation of material to parameterisation, geometrisation, computation, and digital fabrication. For instance, a straight piece of wood exists in the material world, and for the designer to work with wood in the digital and theoretical domain of CAD, a geometric concept must be as-

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121. “Renaissance architectural drawing was perceived as a symbolic intention to be fulfilled in the building . . . towards the end of the 18th century . . . The original architectural ideas were transformed into universal projections that could then, and only then, be perceived as reductions of buildings, creating the illusion of drawing” (Perez-Gomez 1982, 2 and 3).
signed to it—this is geometrisation—and parameters also assigned to the geometric concept—this is parametrisation. Each of these starting points for expression creates its own sector of activity.

In the exploration model, each type of model and its affiliated sector of activity is linked to the next type of model and its sector of activity, and that type to the next one, and so on; the output of each becomes an input to the next in a chain that is broadly articulated towards the outputs, which are then looped back to inform the input (Fig. 5.3). Inputs are broad in terms of media, and outputs are complex by virtue of their materiality and the affordances of the computer-controlled machinery that enables them. These interlinked sectors of activity are essentially different in kind and are not necessarily congruent. For example, the fields of manufacturing and computation are not immediately congruent: it is the designer who must match them up and link them together. To go from computation to materialisation (or from any sector of activity to another) entails a paradigm shift. At some point a model or a sector of activity overflows into the next model and its associated sector of activity: this is the critical point where all of the shifts happen (Fig. 5.4). It is a moment of convergence consolidation and concretion, and most of the significant invention in the design field occurs at this point. Change occurs at the critical point when the key aspects of the exploration are translated and that translation makes them into something else.

Because of the way designers gradually create the exploration model by means of these disparate models and their affiliated tools and mediums they must constantly convert one process into another, then into another and another, and finally the outputs of these models feed back into the earlier ones (Fig. 5.3). This feedback loop varies with the particular design-to-production cycle, which itself varies according to the designer and the mediums. For example, the designer can create automated and direct feedback loops between two digital models, whereas between physical and digital models it is usually necessary to make an interpretive feedback loop.

It is the designer who chooses, for example, one medium or domain of activity over another to initiate the exploration, but the inherent character of the chosen mediums subsequently impacts the rest of the process and the way the designer works with them. For example, the designer may choose to initiate the exploration using material as medium for design. Proceeding in design and moving from a manual model to the digital realm, the designer may then use a 3D scan to represent the physical model as a point cloud, or employ a geometric concept to represent it which disconnects the...
physical model from the rest of the process. As the designer proceeds in design and wishes
to output the digital construct into the physical realm—this is referred to as materialisa-
tion—the designer again has to choose a tool (such as a laser cutter). To create a feedback
loop from the materialised outputs to the early stage, the designer has to translate the result
into a form that can be fed into the earlier stage. Ultimately, the kind of feedback loop creat-
ed in the exploration depends on both how far back into the system the designer wishes to
feed the result, the nature of the sector the result is to be fed to, and previous choices and
selections. If the designer initially used a 3D scan to represent the manual model, then by
feeding back the result to the manual model a harmonious and closed loop can be created.
Conversely, if the designer initially employed a geometric concept to represent the physical
model, feeding back the result to the initial manual model doesn’t make sense, since there
is no direct link between the early physical model and the digital model; in this case, the
loop is created by feeding back the result to the digital model rather than the manual one.

Within the exploration model the designer can move freely between these domains of artic-
ulation and expression and work with different models, tools, and mediums. But the mod-
els, tools, and mediums that a designer chooses to work with each have their own rules and
regulations, which limit the designer’s exploration to their affordances. The designer can
move from a manual model to the keyboard to work with a CAD model, and then to the ro-
botic arm of a 3D printer, and finally then back to the keyboard or the manual model. On the
other hand, if the designer begins by scripting in CAD, the designer cannot then use a pen
to interact with the screen and continue drawing, and would have to print the CAD draw-
ings that were produced with the script and work on the printed page. The next question
would be how to get that manual drawing back into the CAD software.

In order to understand this research, the reader must understand that the models the de-
signers (the author and her students) are working with are of essentially different kinds and
 mediums; they have variances and are constantly in flux, and they are influenced by different
mediums and forces ranging from geometry to materials to algorithms and how all of these
can be explored. In the process of this investigation it is clear that each of these models—if
one isolates them enough, as exemplified in the experiments in Chapter 6—would yield a
specific type of research that is applicable to certain conditions. But the exploration model
that encompasses these models—the exploration model which indeed gradually emerges
from linking disparate sets of tools, mediums, and models—cannot be fully described, as it
moves and shifts according to these preferences and how they are explored (Fig. 5.5).

The exploration model can be seen as being made up of heterogeneous and incongruent
systems of associated parameters and variables (Fig. 5.5): associations such as that be-
tween a physical model and a digital one, or the association of a line to a piece of wood; var-
iables such as the speed of the feedback loop from and output or how far back the feedback
goes into the early stages. For each experiment in this dissertation, the designers design the
exploration domain by making decisions about the models, their links, and the feedback
rates—and indeed for every design project it is the designer who sets the parameters and
the variables for the exploration model.

122. Geometry exists in the mind, while there are applications of geometry in the world. Conversely,
materials such as wood exist in the world and their characteristics can be brought into the computer in
order to work in wood in a digital realm—but this of course remains only a reference to wood.

123. Currently the tools used do not offer multiple interactions to the designer, but perhaps in future
such multidirectional interactions with objects of design will be possible.
This theoretical description is stable insofar as it can identify an infinite range of variance within the exploration model. Each experiment in Chapter 6 can be seen as a materialised instance of this theoretical model, in which linkages and feedback rates are isolated to provide examples. At the same time, just as each experiment can be seen as a materialised instance of the exploration model, it is important to keep in mind that the exploration model that is described here is itself derived and developed from these experiments. The exploration model is in reference to and applicable to the digital design and fabrication of architecture, but because of the emphasis on production at the material level, the exploration model must be resolved its proportional subparts and variants in order to be expressed.

Although the exploration model varies according to project framework, there are two aspects that this exploration model always entails. First, the constraints and potentials of the production, usability, and environmental context of the building and its future site are incorporated into the exploration domain by means of mediums, models, and tools. These constraints and potentials are not automatically incorporated in the exploration domain; it is the designer who selects them and establishes them in the exploration. The earlier the designer embeds a constraint into the process, the more stages of the exploration it influences—that is, all stages of the exploration that come after the stage at which a constraint is incorporated will be affected by it, whereas those that come before are free of that constraint (Fig. 5.6). The question is, how early in the exploration can the designer embed these influential factors, and how can this be done without making the exploration overly rigid at an early stage? Second, the findings of the materialisation are ultimately fed back into the earlier stage of design and influence exploration (Fig. 5.6). The farther back the findings of the materialisation and manufacturing process are fed into the system, the more influential they are. This raises the question of how far back into the process the findings should be fed so as not to restrict innovation.
5.4. The exploration model for each experiment

For each experiment in this dissertation, the designers gradually designed the exploration model. Moreover, they actively chose to design each exploration in a way that was open-ended or goal oriented.

In the experiments presented in Chapter 6, digital fabrication tools are chosen to represent the tools for the actual production context of a prefabricated building. The models are created with a concern for the physics and materiality of a building and its production context (digital fabrication and ways of construction). By means of disparate sets of physical and digital models, their representational mediums, and their links, the different aspects of materialisation are incorporated into different stages of the exploration model (Fig. 5.6). For instance, the selection of a paper strip for manual model making, the use of a developable surface in a digital model, the creation of an FEA structural analysis model, and even the use of CNC milling in Experiment 2 are means for representing and incorporating materialisation criteria into the exploration model: they create subdomains of exploration and reflect the designer’s concern with materiality. As these tools, mediums, and models are linked together, they ultimately feed back to and inform one another. Thus the subdomains of exploration and the exploration model itself are continuously in flux. Ultimately, feeding the findings of the conception-to-production process back to the earlier stages of the process creates a conception-to-production cycle. This cycle is non-linear and recursive. How far back these findings can be fed, as well as what the nature of the feedback loop is, are questions that arise in the first experiment and are investigated in subsequent ones.

Moreover, considering the relation between the designer’s intention, the design intent, and the ideation of design, this research identifies two kinds of exploration: goal oriented and open-ended. In a goal-oriented exploration, the design intent (i.e., the end result or outcome) is prioritized in the process. The exploration model is shaped by the designer’s objective to reach a certain outcome through the selection of mediums, models, and tools, which are employed to fulfil a clear intention: models make it possible for the designer to reach a specified goal. In the open-ended exploration, the designer’s intention (concern) is largely informed by the design process itself and the mediums of design. The designer gives more agency
to design mediums and may end up somewhere unexpected. Here the mediums and the
design process are used for the creation of design ideas and also the exploration itself, and
contribute to developing the ideas. In this kind of exploration, the designer explores a de-
sign idea with the medium.

In neither case is the exploration model neutral. In both cases the designer embeds some
intentions by means of physical models and some by means of digital models, constraining
the exploration, and in both cases the exploration is informed by the designer’s selection
of and ways of working with the algorithm, physical modelling materials, or geometric con-
cept. However, the relation created between the designer and the process differs in the two.
A goal-oriented exploration is undertaken in reference to an end result and the designer’s
initial intention. The designer treats an open-ended exploration as a drifting design prob-
lem that evolves and changes; new and interesting developments that occur in the design
process change the design direction, and the process may end up somewhere unexpected.
In an open-ended exploration the designer may use disparate sets of digital and physical
models to embed various intentions initially, but interdependently linking these models
and being open to what their interaction suggests will achieve results that the designer may
have not foreseen. It is the designer’s approach to the whole process and linking of dispa-
rate sets of digital and physical entities to one another that can create an open-ended or
goal-oriented exploration.

Depending on the way the designers treat the models, mediums, and design process in
relation to ideation, the exploration of the experiments conducted in Chapter 6 is either
open-ended or goal oriented. From the kinds of models used in the explorations and the
kinds of interdependencies created between them in each of the experiments, four kinds of
exploration model are identified: a uniform cycle of digital design to production, an extend-
ed uniform cycle, a hybrid physical and digital cycle, and a multiplex network.

5.4.1. Experiment 1 (Honeycomb): Circular and uniform

Experiment 1 is a goal-oriented exploration and examines the capacity of algorithm for in-
tegrating multiple (structural, climatic, and fabrication) constraints into the design process.
It investigates the integral exploration of form and its material context. This demands early
contributions of expert knowledge in a way that allows the designers to explore architectur-
al concepts and a number of design options at the conceptual stage in an integral manner.
In this experiment, the approach to integration is the creation of digital continuity and con-
formity between different aspects of a building project. Integrating expert analytical and
production knowledge in the development of geometric form is achieved by creating links
between the models and feedback loops between later models and earlier ones.

In this experiment, the exploration is launched from the CAD-geometric model. As will be
shown in Chapter 6, the CAD model, in and of itself, is not enough to formalise a design
completely. Arriving at the design intent is a cooperative effort between the CAD model,
the expert analytical models (in this case CFD and FEM), and the CNC physical model. This
cooperation is enabled by the designer who, with active choice, links the CAD model with
the others involved in the exploration. By creating a digital continuum and feedback loops
between models, the designer enables this cooperation.

This process is called a uniform cycle of design to production because architectural features
and design elements are produced only in the cycle of computational design and the digital
fabrication process. This entails a recursive chronological move from the conceptualisation
of the formal idea by means of the CAD model, to the reformation of the CAD model based on the CAE expert analytical models, and then to the reformation of the CAD and CAE models based on the designers’ evaluation of the CNC-fabricated physical models and fabrication activities (Fig. 5.7).

As every cycle of design to production is completed, the form is augmented and takes on its character little by little (Fig. 5.8). The first instance of the CAD model that a designer creates to conceptualise an idea does not represent a building in its totality. Rather, the architectural features in the CAD model evolve and are reformed by two kinds of links—automated and interpretive feedback loops—between the CAD model and the subsequent models involved in the exploration. The algorithm becomes a means for the designer to explicitly encode constraints and allows the designer to conceptually integrate knowledge from the latter stages of the process into the early design exploration in a generative manner.

The design exploration model for Experiment 1 is goal oriented. The choice of the surface is made based on the designers’ knowledge of the constructability systems that can be found on the digital UV surface—such as contouring, triangulation, waffle gridding—and on their intention to design a complex geometric form that could be fabricated using a two-axis CNC laser cutter. Using the digital surface, the designers could incorporate the fabrication constraints into the exploration model. The “techniques of digital fabrication, which allows the architect to control the manufacturing process through design data” from beginning to end (Gramazio and Kohler 2008, 7) are incorporated into the design by encoding constraints through algorithms and using the digital UV surface. The form and analytical models
are linked and fit together in a nonlinear fashion, enabling the fabrication of a complex geometric form with respect to the site context and the designers’ intention. The algorithm of the form and the digital surface are thus enriched by information related to the constraints of the future site, digital fabrication, construction material, and structure.

5.4.2. Experiment 2 (Strip): Extended circular and uniform

Building upon Experiment 1, Experiment 2 is also goal oriented but questions the wisdom of formalising designs and conceptualising constraints entirely within computer programs and by means of logic (geometry and algorithm). It explores the possibility of formalising the design and conceptualising the constraints partially in physical models and partially in digital models.

This experiment aims at augmenting the exploration by enabling the designers to have direct and intuitive interactions with physical modelling materials in the early conceptualisation stages. The exploration model of Experiment 2 can be seen as an extended version of the previous one, with supplementary manual physical model making now attached to the digital continuum (Fig. 5.9). The exploration in Experiment 1 was initiated by means of a CAD model, and was therefore limited to the geometric language afforded by the software. This means the conception-to-production cycle was isolated within the immediate geometric affordance of CAD and was protected from outside influences. This led the author to rethink the exploration model and push its boundaries beyond the immediate influence of digital geometry.

To ensure constructability and bypass the immediate influence of the geometric language of CAD software at the early design stage, the selection of physical modelling material can be made with reference to the constructability of its full-scale counterpart. In this experiment, the selection of paper strips as model-making material ensures constructability from sheet construction materials. The modelling material, which is in sheet form, incorporates the fabrication constraints of three-axis milling into the early exploration.

Other constraints of fabrication and machining, such as the maximum length of material that can be used in the CNC machine as a result of the size of the machining bed, the thickness of the laminating material, and the

![Figure 5.9. Manual physical model making is attached to the digital continuum cycle. This is not just so that the designers can have contact with modelling materials at the early design stage, but also so that (a) this stage of manual modelling will still be connected to the later digital work, rather than disconnected as it once was, and (b) this happens through the selection of modelling material with respect to the building material and digital fabrication techniques.](image-url)
positions of the joints, are incorporated into the exploration space using a geometric concept—developable surface—and the algorithm. Using algorithm, the designers encode constraints and parameters explicitly. The developed algorithms both generate the developable surface parametrically and enable its reformation in reference to the construction material as curved components with thickness.

While in Experiment 1 the CAD-geometric model was informed only by feedback received from subsequent stages, in this experiment it is not only informed by subsequent stages but also previous ones. Therefore, as every cycle of design to production is completed, the form is augmented and takes on its character gradually as it is informed from two directions (Fig. 5.10). The experiment focuses on the interplay between the computation that occurs in the physical modelling material, digital computation, and material processes in the cycle of design to production.

The exploration model is goal oriented and is materially informed by two kinds of material practice. On the one hand, through the selection and manipulation of the strip of paper, the designers’ intention in terms of constructability of the form and the overall figure of the form identifies the scope of the exploration. On the other hand, the designer’s formal intentions, which are initially manifested in small-scale models and subsequently represented in a CAD model, are reformed with respect to the constraints of digital fabrication tools, construction material, and physical prototyping.

Figure 5.10. The digital geometric model becomes informed by manual physical models and full-scale prototypes.

Even when the fabrication affordance of the CG physical models is considered in the CAD-geometric model at the early stage, they are themselves CAD-driven.
5.4.3. Experiment 3 (Hypar): Branched, incremental, and diversified

Experiment 3 differs from the previous experiments in that it questions the role of ideation, or the creation of the idea, in relation to the design medium, the design process, and the designers’ intention. The exploration models in both of the previous experiments were goal oriented; the models were linked to one another and prepared in reference to an end result. Moreover, the explorations were insulated by the geometric affordance of the CAD-geometric models. In this experiment, the designers give more agency to the mediums of design and are open to unexpected outcomes.

This experiment pushes the role of the physical model in relation to the digital cycle beyond conformation, questioning the necessity of an affinity or likeness between the mediums of the digital and physical models. In Experiment 2, the designers’ concern was the affinity between the strip of paper and the developable surface. Employing the paper strip was not only based on the intention of producing a continual curvilinear form that was constructible, but also on the knowledge that all of the forms suggested by the paper strip were representable in CAD by means of a digital developable surface, as there is a great affinity between the forms the paper strip and the developable surface can take on. In contrast, Experiment 4 questions the significance of the kind of interdependencies the designer creates between the design mediums—affinity versus incongruity. Instead of one medium, Experiment 3 begins with two modelling mediums—hyperbolic paraboloid geometry and a sheet of paper—both of which can incorporate the fabrication constraints through their inherent properties. The designers intentionally choose mediums that contain the constraints of fabrication from flat material, but they do not impose their formal intention onto them; rather, they work with the mediums and explore opportunities. In other words, whereas Experiments 1 and 2 began with surface and material, respectively, as starting propositions for the design intent, Experiment 4 begins with two mediums, geometry and material, which are not intended to stand in for the design intent: instead, they confront one another.

In the previous experiments, architectural features were produced in the course of the integral computational and digital fabrication process by means of feedback loops whereby the synthesis of the results from later stages was fed back to earlier ones. This is also true for Experiment 3, but here architectural features and design elements are also produced by the bidirectional fusing of the mediums (computational geometry and physical modelling material) and processes (geometric computation and material computation). The feedback loop is not the only way to create new features; confronting the heterogeneous mediums—hypar surface and paper—in a bidirectional fashion leads to the invention of the fold as a new feature. This feature was not initially intended by the designers. Since the fold is not inherent in either the paper or the hypar, it requires the production of a new geometric model, which then is reformed by the latter stages of the design to production cycle by means of the feedback loop, evolving over time (Fig. 5.11 and 5.12).

In this experiment geometry and algorithm are taken out of the computer and implemented in the material world. The experiment emphasises the role of mediums in the exploration, rather than the categories in which the mediums are explored—categories such as digital versus physical modelling environments, or structural models versus geometric models. It pushes towards breaking out of categories and emphasises the ways the mediums geometry, material, and algorithm are used.
In this experiment material effects are embraced as design drivers. The design exploration is open-ended and is treated as a drifting design problem. New problems emerge for which new solutions are sought, driving the direction of the design exploration. For instance, the invention of the fold leads to the invention of the folding moulds, which leads to the casting of the gypsum and concrete components and the production of the hyperbola of revolution structure presented as Experiment 4 as a third element that holds all these secondary elements together.

When working with students, the author has noticed that some think that they must begin with a good idea and then materialise it, postponing the action of design while waiting for the idea to emerge. But sometimes in design there is no particular idea at the beginning; the idea emerges gradually out of the process.
5.4.4. Experiment 4 (Paraboloid of One Sheet): Parallel and bidirectional

Experiment 4 emerges from and at the same time departs from Experiment 3. It questions the role of elements of the exploration as design drivers, the directions of influence, and consequently the direction of the propagation of changes in the exploration model. By doing so it breaks away from the cycle of design to production as well as from the separate categories of digital and physical. It questions the share of the power given to models involved in the exploration to drive the exploration—whether by the tools that are used or by the particular way the designer employs them in the design process.

By using the quality of the manual physical models as free movers and increasing their level of engagement throughout the design process, this experiment explores the benefits of bidirectional influence. This is done by creating bidirectional and non-automated links between the physical and digital models in the cycle of design to production, with the designers sensing and feeding back the data (Fig. 5.13). Physical models are developed to change the direction of design and to suggest construction material and strategies (Fig. 5.14). By examining the capacity of the parametric-associative system for bidirectional physical-digital modelling and considering the compatibility of the physical model with the parametric-associative digital construct, this experiment suggests future developments of the parametric-associative system. Such developments might allow changes in the direction of influence in the hierarchical dependencies and emphasise the kinetic quality of physical models. For instance, a kinetic paper model built with respect to the digital construct could interact with the screen and the parametric-associative model. Moreover, what if the hierarchical dependencies of the geometric model could change throughout the design process when the designer found out about other influential factors?

CAD tools are subject to continuous change and evolution. This experiment emphasises the fact that the designers’ expectations and way of design are as important as the rules offered by software.
5.5. Reflections

The exploration models that are developed from each experiment in Chapter 6 comprise different classes of mediating artefacts (models, mediums, and the links between them) which are disparate but fit together or can be bridged. As will be shown in Chapter 6, one thing rolls into the next—one sector of activity into another, one medium into another—through translation, conversion, connections, and hybrids. Two things give rise to a new thing.

Explorations begin with the designer’s active choice. The moment the designer selects either a hardware device (e.g., a 3D printer), one medium instead of another (e.g., a NURBS surface instead of a mesh surface), a kind of model (e.g., a digital structural analysis model), or a mode of operation (e.g., manual experimentation, machine experimentation, or logical operation), the designer makes a decision and moves away from uncertainty. At this moment the exploration model begins forming and finding its relations. Once a model is created, it changes everything; it moves the exploration to a different phase: the phase of formation. Every individual model has the ability to reduce uncertainty and anchors the exploration to a particular aspect that concerns the designer. The designer also sets the linkages throughout the process, allowing innovation to emerge in a non-linear fashion—the exploration model is non-linear. Innovation happens gradually at different moments, in the gaps and discrepancies that are tied
The designer increases the potential for significant invention by diversifying the kinds of models, ways of linking the models, and ways of treating the process. The designer is a part of the exploration model and can decide to stay at one point longer than another.

The exploration models developed in this dissertation entail incongruity and diversity. In each exploration, innovation is encouraged by bringing together models, mediums, and activities that are diverse and different in kind. It is in bridging the disparate sets of activities that significant invention occurs. The exploration model that contains incongruity and diversity will support innovation by virtue of the gaps between and discrepancies among different representational mediums. For innovation to occur, one must provide sufficient diversity and ambiguity. In the experiments above, significant design invention occurs in bridging between heterogeneous mediums and processes, in moving from the whole of a form to its parts and vice versa, and in switching scales, mediums, and processes. These are the moments when change happens and significant features appear. For instance, when the scale of making is changed, the way of making and the kinds of materials used change with it. When moving from small-scale to large-scale making, one might move from a paper strip to a wooden strip and from twisting to lamination, or from a fold in a sheet of paper to a hinged connection or joint-and-plate system connecting pieces of MDF.

The constraints and influences of the manufacturing process, construction material, construction logic, and site are incorporated into the exploration model by means of disparate mediating artefacts. However, incorporating constraints does not mean the design process has to be goal oriented. Incorporating constraints can be part of an open-ended or goal-oriented approach through the way the designer links the models (which incorporate the constraints) and treats the exploration. How early the designer can incorporate constraints into the exploration, the possible variations of this incorporation, and how the mediating artefacts inform the method, the process, and the architectural idea itself are questions that are explored in the experiments conducted as part of this research.

It is by means of models and their representational mediums and affiliated tools that the designer embodies the constraints of the materialisation of a building into the exploration model. An important question is how early in the process the designer can embed and incorporate the constraints into the exploration model without limiting the potential for innovation. Another question is what are the ways of linking these models and their mediums so that the new interdependencies between them increase the potential for significant design invention. These questions are examined in the experiments presented in Chapter 6.

The materialisation of each design-to-production cycle ultimately feeds back into the earlier stages of design and influences the way one designs. How far back these findings can be fed, as well as the nature of the feedback loop, is another question that arose in the first experiment and was investigated in subsequent experiments.

Finally and most importantly, significant innovation relies on the designer’s coordination of mediating artefacts and ability to resolve the persistent problems that emerge as a result of coordinating things that are not immediately congruent, but become congruent by means of technical or nontechnical bonds.
To the author, innovation involves combining elements in new and unique ways that are relevant to architectural values and useful for people. It is ingenious ways of employing digital computation and digital fabrication that bring about novel discoveries in design. Discussion between the author, Benjamin Dillenburger, and Axel Kilian in the final seminar event of this PhD, University of Toronto (Toronto, Canada), 4 June 2015.
Experiments
Context of the experiments

The experiments discussed in this chapter were developed in the context of the Design and Making studio and Advanced Seminar graduate courses directed by the author and Hamia Aghaieemeybodi. The studio, which the author founded as part of her doctoral research, was taught to graduate students in the Architectural Engineering program at Lulea University of Technology (LTU). The Advanced Seminar courses, which were developed around the author’s doctoral research, were taught to graduate students in the architecture program at the Royal Institute of Technology (KTH). Experiments 1 and 2 were developed as part of the Design and Making studio, and Experiments 3 and 4 were developed as part of the Advanced Seminar courses.

Each experiment was designed and realised by the author and Hamia Aghaieemeybodi with students from LTU and KTH, who are credited in the Acknowledgements. In Experiment 4, the exploration of the concrete components and dynamic formworks was further developed in collaboration with Oliver Tessman and his graduate students in the architecture program at KTH. The analytical expert models used in Experiments 1 and 2 were developed by the author in collaboration with Pooya Vahdati, mechanical engineer (CFD), and Giuseppe Giugge Caprolu, Structural and Construction Engineer (FEM).

Economy

All of the experiments were realised with extremely tight budgets. In most of the experiments, budget constraints were the most important driving force during the design and production phases. Funding for realising these experiments was obtained both from within academia and externally from industry by the author in collaboration with a number of students (details about the funders can be found in the Acknowledgements).
Order of the experiments
The experiments are presented in chronological order according to their date of realisation. Each experiment was a stepping stone towards the next one. They were not meant to be compared to one another; rather, each was built upon the last in an exploratory fashion. The first experiment was conducted in accordance with the common way of practicing computational design and digital fabrication in architecture; it was framed to exploit the potential of digital tools and to push them to the limit of their capabilities. By the time it was completed, questions had arisen that formed the set-up and framework for the next experiment. The same pattern was repeated through to the last experiment: problems, questions, and curiosities that arose in earlier experiments formed the bases for subsequent ones. As the author moved through these experiments and expanded her knowledge by practice, her way of treating the exploration and the relation between computational geometry and the enforced material geometry changed. As a result, both the frameworks of the experiments and the author’s understanding has shifted and evolved over time.

Practice-based research
This research is practice-based. As presented in the introduction, in practice-based research new knowledge is achieved “partly by means of practice and the outcomes of that practice” (Candy 2006, 1). Practice-based research positions artefacts, processes, and practices at the centre of research. The knowledge that is produced here relies on the actual practice of the author as a design practitioner, educator, and researcher. In this dissertation, originality and contribution to knowledge are demonstrated through creative outcomes in the form of design and making and the presentation of the results. While the context and significance of the work are described in words, a full understanding can only be obtained with direct reference to the process of the experiments and their outcomes.
Figure 6.1.1. Honeycomb prototype, 6.2 metres high. Photograph by Pooya Vahdati.
6.1. Experiment 1 (Honeycomb):
Circular and uniform exploration model

Figure 6.1.2. Honeycomb prototype, 3.0 metres wide.
Photograph by Pooya Vahdati.
6.1.1. Introduction

The process of creating architecture involves many constraints. These constraints influence the designer’s decision-making and can be a driving force for design. By looking back to history, Michael Cook has identified material, ability, and need as the key factors influencing the form of what human culture has made (Cook 2004, 40–49). What we can find around us as building materials and our ability to assemble them predict the performance of buildings in the real world; our reasons for needing a building, from safe shelter to something of utility or beauty, play active roles in creation of architecture.

Alongside changes in social needs and materials, the development of computer-aided design (CAD) technology and affiliated computation techniques has been specifically changing our ability for the *immaterial generation and computation of form*. The integration of CAD with computer-aided engineering (CAE) enabled us to predict the performance of form in the physical world. The ability to directly feed results from CAE analyses back into the CAD process has also influenced the generation of form based on the prediction and simulation of material behaviour in the physical world and incorporation of constraints. The computation of form can now be done integrally with the active forces in its future site context.

At the same time, the development of digital fabrication tools and computer-aided manufacturing (CAM) systems has made the digitally aided materialisation process a true counterpoint to CAD processes in architecture. This relation has enabled the augmenting of the theoretical space of computational form (integral CAD and CAE) with empirical experimentation: the precise realisation of complex forms and the instant prototyping of their parts within the design process can be evaluated and fed back into the theoretical space in order to augment the form. This convergence of CAD and CAM technologies has led to a symbiotic relationship between the digital and physical worlds.

By synergising tools across the building disciplines, designers can have comprehensive and integral design-to-production processes: an “integrative design” (Kolarevic 2008, 656) for the design of buildings and the built environment, in which the generation of form is done with reference to the constraints of forces in its future production or site context (Fig. 6.1.3). In this broad context, the design is driven by purely technical constraints (structural, thermal, or acoustic factors, among others) or nontechnical ones (spatial, aesthetic, social, or cultural factors, among others). Most of the developing paradigms have a linear, optimal solution to the efficiency of one constraint, such as structurally optimal solutions, while the synthesised use of digital technologies offers a “comprehensive new approach” (Kolarevic 2005, 7) that considers many aspects of the design of our built environment. As Branko Kolarevic has noted, the “comprehensive new approach” is offered by “the digital technologies of qualitative and quantitative performance-based” approaches (Kolarevic 2005, 3). The “performance-driven paradigms” are “blurring the distinctions between geometry and analysis, between appearance and performance” (Kolarevic 2005, 7). Although different performance-driven paradigms are separated, they unavoidably originate from and influence each other—and since every architecture project has specific criteria, the criteria change over time and “there is no optimal fixed solution once and for all” (Rahim 2005, 183).
Designing and prototyping the *Honeycomb* pavilion was an experimental project to investigate the computation and generation of form through instant nonlinear circular feedback received from disparate sets of digital and physical models that incorporated constraints (usability, structural, fabrication, climatic, economic, and material constraints, among others) into the exploration. Constraints played an active role in the design and realisation of this project and became a driving force for decision making. Constraints were modelled in a way that made them integral to an evolving architectural expression of the project.

### 6.1.2. Project framework: defining constraints and challenges

In this project, the spatial articulation and structural system emerged in response to the usability framework, climatic characteristics of the site, available production technology, and affordable material.

- The usability framework was to design a temporary furniture-like pavilion that would enable relaxation (sitting, lying, leaning, or standing) in all seasons.

- The site is located in the city of Lulea, in northern Sweden, and is characterized by extreme seasonal climate changes. The extreme conditions and absence of atmospheric precipitation, sun, wind, darkness, light, cold, and heat in different seasons, especially winter and summer, are important climatic factors to control in stimulating people’s outdoor living and activities.

- The available production technology was a CNC laser-cutting machine.

- Possible material choices were 3.2 mm and 7.0 mm Masonite, 5.0 mm high-density (HD) Masonite, and 6.0 mm plywood. These materials were candidates in relation to budget and machine capability.
6.1.3. Spatial articulation and structural system

The 3.0-metre-wide, 7.0-metre-long, and 2.6-metre-high prototype of the pavilion is built out of 2976 geometrically different parts, made of only 3.2-millimetre-thick Masonite. These parts include 1248 plates and 1728 joints nested to produce six-sided cells tracing a computed double-curved surface. Providing an enclosed space, part of the structure is lifted from the ground to form a free-spanning shell (Figs. 6.1.1 and 6.1.2). Breaking the northeast wind, it touches the ground topography and is intended to be covered by glass panels which have never been fabricated (Fig. 6.1.4). To provide seating opportunities, the structure curls inward (Fig. 6.1.5); in contrast, the other end of the structure narrows to cover itself from wind and is concave to provide opportunities for lying down (Fig. 6.1.5).

The design of the polygonal structural system of the pavilion is intended to achieve economy in terms of material, and is inspired by the honeycomb pattern in nature, which yields natural structures with minimal density and achieves relatively high out-of-plane compression and shear properties. A structure that has the geometry of a honeycomb minimizes the amount of material used to reach minimal weight and minimal material cost. Since the material used (Masonite) has poor compression and shear properties, nesting it in the honeycomb-like pattern improves these properties in the whole structure. The six-sided polygons tile the surface with minimal surface area.

Figure 6.1.4. Digital rendering of the pavilion, showing the curvilinear wooden structure and partial glazing. The glazing was intended to keep the wind from penetrating the structure. Due to economic limitations, the glazing was never realised in the built prototype.
Figure 6.1.5. Top view, section, and elevation drawings of the pavilion illustrate the relation between its form and its usability.

127. The tight budget did not permit the fabrication of glass for the realised prototype.
6.1.4. Formal diagrams of force and requirements

The design exploration began with representing the constraints by means of diagrams. The representations of these diagrams were such that they contained “physical implications” and shared elements with diagrams of form, that is, diagrams that give “a description of formal characteristics” (Alexander 1964, 87). As noted by Christopher Alexander, “a diagram which expresses requirements alone or form alone is no help in effecting the translation of requirements into form, and will not play any constructive part in the search for form”; a requirement or force diagram is useful if it “contains physical implications, that is, if it has the elements of a form diagram in it” (Alexander 1964, 96).

The study of users’ behaviour in winter and summer showed that they would like to be exposed to direct sunlight in both seasons. They would also like to have fresh air in all climates and do not mind the temperature differences, however the strong winds are not desired. Based on these requirements, a requirement-spatial diagram of enclosed but porous spaces and exposed spaces was drawn in a way that would contain physical implications. A sine-like curve was drawn as a form diagram that would correspond to the requirement diagram and as a representation of a medium that would enable both enclosure and exposure. The sine curve was a useful formal diagram, as it foresaw the functional consequences (Fig. 6.1.6). The form diagram was put into contact with external forces through a formal-force diagram (Fig. 6.1.7).

6.1.5. Integral computation and materialisation

To begin the exploration by means of a CAD-geometric model, a digital freeform surface that could easily assume any sine-like form was chosen as a starting point and formal proposition for design. An algorithm was developed to generate the potential forms of the surface. To do so, a way of generating the surface together with influential values and parameters was defined in the definition of surface. The digital surface was generated from two parameterised NURBS curves, whose changes would propagate to the figure of the surface (Figs. 6.1.8 and 6.1.9). Changes in the parameters were influenced by the data resulting from a wind simulation model.

Integral computation and materialisation began with computing form with reference to the active forces of the site context.

**Simulation model: CFD expert analytical model**

In search of a structure with a tempered environment, form was conceptualised with respect to the active forces in the site context. The designers sought to create an interdependency between the form of the surface and the wind currents of the future site in such a way that their cooperation would offer a tempered environment for the structure. Wind currents would not enter the structure’s inner space and would not accelerate around it. To do this, the algorithmic definition of the surface had to be reformed based on new influential values and parameters. The following steps were taken:
(1) The behaviour of the wind at the site was simulated computationally using computational fluid dynamics (CFD). (2) Significant parameters of the surface’s form with respect to wind behaviour were found—this was done by importing an instance of the sine-like surface to the CFD model and analysing the wind behaviour around this instance. Based on the designers’ observations, simulation of the wind behaviour around this surface was interpreted and then used as a guide for reparameterising the surface in the CAD-geometric model in such a way that form would be altered by the information received later from the wind-current simulation. (3) Once reparameterised, a circular feedback loop between the CAD and CFD models was created that would then generate alternative forms of the surface (Fig. 6.1.10). This is a generative mode of using computational fluid dynamics (CFD), in which the designers identified parameters within the surface to be altered by the wind currents, in order to use the result from the wind simulation as the drivers of form alteration. The guiding question of our search was, what is the range of desirable forms or figures of a surface when it is in contact with wind currents?  

The CFD expert analytical model presents information regarding the behaviour of the fluid dynamics within the site. The model was first used as an analytical model to investigate the behaviour of wind within and around the surface forms that were placed in the simulation model. From this initial analysis, the behaviour in relation to an alternative thickened and sine-like surface was studied. These studies enabled the designers to identify which physical characteristics of the surface (height, width, smoothness or sharpness, enclosure and exposure, etc.) must be parameterised and linked to the simulation model in order for it to act generatively rather than analytically.

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128. Similarly, “a form diagram becomes useful only if its functional consequences are foreseeable, that is, if it has the elements of a requirement diagram in it” (Alexander 1964, 87).

129. An algorithm was designed that generated four parameterised NURBS curves (Fig. 6.1.8). To generate the freeform surfaces, every two curves were lofted together (Fig. 6.1.9). To create a solid, the edges of the two surfaces were lofted together. The relations of these curves to each other defined the thickness, width, length, height, and consequently the shape of the pavilion, which was later altered by the structural iteration.

130. Surface is like a raw material here. Like soap liquid, it does not yet have a shape but it does have its own inherent properties.
The important thing in this model was to define the wind behaviour in relation to the geometric parameters of the surface in order to further enhance the form. A virtual wind tunnel was designed and different wind velocities were given in ANSYS Fluent software. The simulation was run and the behaviour of wind was studied in the X-Z and X-Y planes (Fig. 6.1.11).

A number of potential forms of the surface were evolved to control the wind flow (Fig. 6.1.10). While the primary form of the surface let the wind through, the later potential forms diverted the wind from blowing inside (Fig. 6.1.12). However, in all of them, when the wind met the object’s corners its speed increased by about 9.5 m/s.

The wind pressure over the structure was studied (Fig. 6.1.13) to investigate the lifting up of the structure. However, this analysis was found not to be useful, because (1) as the designers proceeded in design, the character of the form changed dramatically as result of the design and arrangement of its components, and (2) compared to the structural load, pressure was not a major factor affecting form finding. Wind pressure was thus removed from the equation.

Figure 6.1.11. The behaviour of the wind when meeting the geometry is simulated and analysed in the X-Y plane (left) and X-Z plane (right).
Figure 6.1.12. The images illustrate two extreme wind behaviours that led to the generation to two extremely different forms for the structure. In both of the above images, the wind velocity increases at the sides of the geometry, but in the left one it is diverted from blowing inside, whereas in the right one it is blowing into the geometry.

Figure 6.1.13. The images illustrate the average wind pressure over the surface for the two variants of the form. The wind pressure is -23 Pa for the form illustrated on the left and 10 Pa for the one illustrated on the right.

"ANSYS Fluent software contains the broad physical modeling capabilities needed to model flow, turbulence, heat transfer, and reactions for industrial applications ranging from air flow over an aircraft wing to combustion in a furnace, from bubble columns to oil platforms, from blood flow to semiconductor manufacturing, and from clean room design to wastewater treatment plants" (ANSYS).
Fabrication constraints as design drivers

In the search for computable surfaces whose materialisation was possible given the affordance of the fabrication tools, the logic of fabrication was incorporated into the logic of surface, augmenting the theoretical and descriptive space of design. This entailed capturing the constraints inherent in the digital fabrication tools and then correlating them with the mathematical logic of digital surface. The fabrication machine used, a two-axis laser cutter, only offers perpendicular cutting of material sheets with no angled cuts. Knowing this, coupled with the inherent mathematics of the NURBS surface, U and V vector coordinates, and splines, allowed the designers to convert the surface and map its materialisation techniques: tessellating, contouring, and sectioning (egg-crating or waffle-gridding) (Fig. 6.1.14). These surface conversion techniques can be seen as technical bonds through which the designers correlated the form of the digital surface with the fabrication ability of CNC machinery.

Using the CNC laser-cutting machine, instances of each of the surface conversions afforded by the fabrication technique were materialised in cardboard. Presenting tangible results, the cardboard physical models were helpful tools for manifesting the different formal arrangements. The by-product ornamental features and structural pattern resulted from the fabrication and surface-conversion techniques. Each physical model served as a diagrammatic representation of the integral structural load path; each of these formal arrangements suggests a particular pattern of structural load-distribution and convergence that was studied and mapped through visual material study (Fig. 6.1.14).

To further the design exploration’s convergence towards full-scale production, the designers looked for a construction material to replace cardboard. The use of the two-axis CNC laser cutter together with the limited budget constrained the material choice to Masonite. Masonite is an engineered composite hardboard made from wood fibres and is produced in sheets of a certain size at different thicknesses. Being a composite wood panel, Masonite has very poor compression and shear properties compared to timber. Compared to other composite wood panel material, Masonite has a high bending strength, tensile strength, density, and stability due to the use of long fibres in its production (Wikipedia 2015).

In the search for an affordable and structurally feasible mode of surface conversion, the path of structural loads suggested by the arrangement of parts within the physical models was judged with reference to the cost and structural properties of Masonite and in the context of the overall form. Considering the overall form of the generated surface, Masonite plates were judged too weak to span a large distance like a beam; they therefore had to be laid over each other in pieces creating a massive structure, attached together as a long span beam using lamination, or cut into pieces and nested using a tessellation technique. Layering and lamination pattern methods were more costly than triangular tessellation due to the amount of material needed, so the formal arrangements resulting from contouring and sectioning (egg-crating) were eliminated as options. While tessellation was found to be a more suitable technique, the triangular pattern it produced...
was still very costly. Searching for a way of optimising the triangular tessellation, the designers found polygonal tessellation to be an alternative that would use less material (and thus be less costly) and offer a structurally stable formal arrangement.

The six-sided polygonal pattern was chosen because the perimeter of a hexagon uses the least amount of material to tile a surface. Comparing the design with those found in nature, a honeycomb structure was found to be the best match for the material constraints of this project. The honeycomb form—found in beehives, for instance—provides a structure with minimal density and achieves relatively high out-of-plane compression and shear properties. This would strengthen the tension and compression properties of the overall structure. Structures that have honeycomb geometry also minimize the amount of material used, thus achieving minimal weight and minimal material cost.

**Geometry as a design driver**

By means of a bond—the polygonal tessellation—the initial computational model that computed the sine curves of the surface was augmented to embed the constraints of the materialisation stage. The surface was converted to a honeycomb-like geometric construct. This was achieved by populating the surface with polygons, extruding them towards a number of focal points, and then trimming the conical-polygonal components with the secondary surface to create polygonal components packed together (Fig. 6.1.15). To make a digitally fabricated physical model, each component was initially unfolded to produce the geometry for CNC laser cutting. Strips were cut off the cardboard, and each component was built by folding a strip at five positions. The folding of the angles was enabled by cutting halfway through the cardboard and then connecting the two ends of the strip to each other (Fig. 6.1.16). The polygonal geometry was given the role of design driver and the CNC fabricated components were geometrically enforced in accordance with the designers’ intention.

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132. The mathematical expression of the logical surface (topological medium). Logical surfaces are defined by U and V vector coordinates; an example is a spline surface that is converted to a triangulated surface.

133. The techniques were explored and mapped regardless of the overall form of the surface.

134. However, modelling with cardboard proved unhelpful when scaling up the project. Scale prototyping and understanding material behaviour were crucial, as this process revealed what it was actually possible and economically feasible to create.
Aspects of construction as design drivers

From the standpoint of construction and stability, the folds necessary for transforming the cardboard strips to take on the geometry of the polygonal components were not a feasible feature for the full-scale component made from Masonite. Revisiting the geometry of the paper components with a mind to constructability led to the development of the joint and plate system (Fig. 6.1.17). To embed the logic of construction into the geometry of the components, they were broken down into two families, namely joints and plates. The conversion of the components to joints and plates led to the rearrangement of the form and the hierarchical dependency of geometries. As result of the material and fabrication constraints, the design of the joints and plates was narrowed to flat components with no angled interlocking moment (Fig. 6.1.17, third image). Initially, the designers tried to design flat finger joints within the plates, however as result of material weakness this design option was omitted.

The next iteration of the computational geometric model embedded the plate and joint system. In this model, the designers identified the elements of the formal arrangement (joints and plates) as well as their hierarchical dependencies on one another; the geometry of the joints was built upon the geometry of the plates, and the geometry of the plates was built upon the polygonal pattern which was initially populated over the sine-curve surface. This computational geometric model was refined and altered using two parallel feedback loops, namely structural relaxation and physical prototyping, with two parallel conditional check lists, namely material cost and material cutting time. This is an integrated cycle of design of geometry-simulation-physical prototyping (Fig. 6.1.18).

The algorithm was revised to generate the form from joint and plate components. To allow later refinement of the CAD-geometric model when feedback was received from physical prototyping, structural relaxation, material cost, and fabrication time, the geometry and parameters for the joint and plate components had to be defined based on the influential values (Fig. 6.1.18). To define the geometry, variables, and parameters of the joints and plates, the designers asked the following questions:

• What shapes can the flat joints assume so that they are aesthetically desirable while being strong enough to hold the plates in extreme load conditions (Fig. 6.1.19)? And how small these joints can be?

• How far from the edges of the plate-components should the joints be placed, so that the structure is stable (Fig. 6.1.20)?

• What are the maximum and minimum angles at which a joint component can hold the plates together without breaking?

• How deep must the cut-outs for the interlocking moment of the joints be to hold the components tightly without losing their own strength? (If the cut-outs are too deep, the joints will be weak and will not keep the plates stable.) (Fig. 6.1.20)

• To define the domain of components that would populate the surface based on their size (minimum and maximum perimeter), the designers asked what is the largest polygon perimeter that the plates could be built into without losing stability in the plates and the whole system. In addition, how deep could a plate be without weakening? Of course, larger polygons were desired to reduce material use.\[136]
Figure 6.1.17. These images illustrate the shift in construction solutions once the material and scale of making are changed. The first images are the realisation of polygonal components by paper and cardboard, the middle ones show the failure of using finger joints as a solution for realising the polygonal components when using Masonite, and the last images illustrate the joints and components as a solution to realise the geometric component when using Masonite.

135. This was done by visual material and comparison study. In parallel to visual study, the variant conversion of the computational surface was linked to a cost algorithm that counted the used surface recognised as material and output the cubic area of material used for each type of arrangement.

136. Domain refers to the maximum and minimum size of each polygon’s perimeter; the minimum and maximum are set by the designer. With this domain range set, the software will not allow it to be exceeded as the designer explores form.
Figure 6.1.18. This image illustrates the variations in the number of parts and their dimensions based on the synthesis of the structural and prototypical analyses. The synthesis of analyses was a negotiation between disparate constraints. For example, for structural stability the number of parts increases but at the same time this leads to an increase in the material used and consequently increased cost.

Figure 6.1.19. These images illustrate two examples of different shapes that joints could have been given.

Figure 6.1.20. This image illustrates the parameters of the parts (joints and plates), which were examined by the design team in relation to aesthetics, cost, and structural stability: the maximum and minimum length (L) and width (W) that these discrete parts can take and the maximum an minimum depth (d) and thickness (t) for each interlocking cut, as well as the shapes of the parts, for example how curved the sides of the joints can be.
Feedback loop between geometric and expert structural analysis models

The geometric model gave no information about deformations due to material dead load or external forces (i.e., wind lifting). When it comes to physical balance and deformation of material due to dead load or external forces, the geometric model is only an abstraction.

In search of the equilibrium state, the geometric model was linked to the finite-element simulation model. A generative or informative mode was sought. The generative approach makes use of the finite-element models to generate the form, rather than only analysing it. By creating links and feedback loops between the geometric model and finite-element model, the packing of the components on the surface and the overall form were dynamically relaxed (Fig. 6.1.21). Dynamic relaxation is a numerical method for finding the equilibrium state of a form—the state in which all forces are in equilibrium. The results from finite-element analysis were fed to the CAD model, iteratively changing the geometry (it oscillated) until it reached an equilibrium state. In this case, the finite-element analysis (FEA) was done using Abaqus CAE software (Fig. 6.1.22).

Figure 6.1.21. Using the dynamic relaxation method, the finite-element model informed the distribution and density of the polygons on the surface as well as the surface’s overall form. By selecting a network of edges, the FEA results were used to dynamically relax the components across the surface.

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137. Finite-element models are analytical and simulation models. Finite-element analysis (FEA) uses the finite-element method (FEM) to simulate how a geometric form reacts to real-world forces when it is materialised. For example, it can calculate the stresses and tension of parts and assemblies under internal and external force loads.
The designers created a direct link between the dynamic relaxation of the overall form, the dynamic relation of the polygons on the surface, and the depth of the structure. The depths of the nested components were altered in such a way as to transfer and bear loads while enabling sitting and lying on the structure. The digital tessellation at the two ends of the object was thickened to improve the balance of the structure. To support the whole weight, certain areas were altered—thickened, extruded, or made shallower. However, the altered formal arrangement from this iteration loop was only a rough estimation of desirable structural behaviour in the physical world, since many parameters were missing from the digital bounding box of the finite-element model.

Particular areas of the texturing were identified and associated with the alteration to maintain the balance of the pavilion and act as the main load-bearing areas. These sets of zones, whose margins formed an essential line of the structure, are neatly camouflaged with the ornamental and textural quality of the surface. There are no beams or columns in a conventional sense, no wall and no roof. “In” is “out,” and “out” is “in.”

Scale prototypes of parts

Once the formal system (joints and parts and their hierarchical dependency) was determined, alternating between the computational model and the physical prototype was essential to refine the system. An important example of this was the joints, which at first were to have curved sides but through prototyping were found to be too weak to support the whole weight of the structure, especially when more than twenty plates were nested (Fig. 6.1.23). The result from prototyping was interpreted and then fed back into the computational model, resulting in changing the curvature of the joints’ edges. After a number of iterations between the physical and digital models, the edges were straightened to allow a tight fit. In parallel, experiments with different joining positions were carried out to find a stable solution. Eventually, it was discovered that putting joints at each corner gave the structure stiffness and reduced sag (Fig. 6.1.23).
The structurally poor material and constraints of the fabrication equipment had the greatest effect on design decisions. Material properties such as tensile and compressive strength are poor in Masonite, which led to the omission of long-span plate components at certain locations where the external and dead load forces would break the plates (Fig. 6.1.23).

**Cutting time: Algorithms for time and cost calculations**

To choose a material that fit the project’s limited time and budget, four materials were tested in the fabrication lab: 3.2 mm and 7.0 mm Masonite, 5.0 mm high-density (HD) Masonite, and 6.0 mm plywood. There was a direct correlation between the cost of the material and its thickness: thicker material cost more. In order to measure the cutting time with the different materials and thicknesses, the laser power was kept constant and the cutting speed was optimized in relation to material thickness. Due to the limited time and budget, the choices of material were listed in order of preference as: 3.2 mm Masonite, 7.0 mm Masonite, 5.0 mm HD Masonite, and 6.0 mm plywood (Figs. 6.1.24 and 6.1.25). In order to estimate material cost and cutting time, these results were fed into the economy and time-setting algorithms, which were directly linked to the algorithm of the geometric dependencies of form.139

138. In order to calculate the dead load, the relation between these parts had to be defined in the CAE model. To avoid defining the relation between plates and joints manually, a script was written. This automation accelerated the process of linking the CAE and design models.

The pre-processing or modelling stage was done in CAD software, and then imported into CAE software. Since the parts were cut from a sheet of even thickness, the input file to CAE software could be specified as surfaces rather than as a solid. In the processing or FEA stage, specialist knowledge of material properties, constraints, and mesh properties was needed to set up the analyses. The last stage, post-processing or generating the report, image, and animation, was also dependent on specialist knowledge in order to read the analyses. The results from finite-element analyses (Fig. 6.1.22) were further interpreted and translated to define the boundary of the variables assigned to parameters of the geometry.

139. The parametric-associative representation of the geometry.
The economy algorithm gave live feedback about the cost of the design model for each Masonite thickness (Fig. 6.1.26). It calculated the integral areas of the plate and joint components and then multiplied the total areas by the cost number for each material, therefore calculating material cost for the project for each material option.

The cutting-time algorithm gave feedback about the fabrication time of the design model for each Masonite thickness. It first calculated the total perimeter of the plate and joint components of a given design, then multiplied the result by the cutting time per second for each material.

These two algorithms were directly linked to the fabrication algorithm that generated the geometry of the parts to be fabricated. For every design alteration, the geometry of the parts changes; this link enabled the estimation of the cost and cutting time for each design alteration and material. The challenge was the choice between a material’s cost and its performance. Sometimes different material thicknesses had to be tested in order to achieve the highest performance (Fig. 6.1.27). Changing the thickness of a material could strengthen its performance, but would lead to changes in cost prediction. The economy algorithm made it possible to get live feedback about cost (Fig. 6.1.26). In many cases, design decisions had to be rethought and changed based on the physical prototyping result as well as the cost of the project.

**Performance of fabrication tools and material imperfection**

The performance of fabrication tools and material imperfection called for design solutions. The production of the fabricated kits was highly dependent on the performance of the CNC laser-cutting machine. Laser cutting is based on the use of thermal energy to cut the material by melting or burning; the machine is used in two-dimensional fabrication and the cutting tool moves along two axes in relation to the work piece, which can be sheet material. In this experiment, various parameters such as the unevenness of the work piece (Fig. 6.1.28) and cutting table led to variable burn of the material. This increased the possible errors in the intersections between joints and plates. To compensate for this, plastic ties were introduced in detailing (Fig. 6.1.29). Consequently, a cylindrical perforation was introduced to the geometry of the plates and joints in the computational model.
Difficulties in the construction process

The fabrication process—the simultaneous assembly of the pavilion’s parts and the construction of the scale prototype—took place off-site. The laser-cutting machine allowed the fabrication of 2976 geometrically different parts, 1248 plates, and 1728 joints (Fig. 6.1.30 and 6.1.31). These kits were cut out of 122 Masonite sheets of 3.2 x 800 x 1100 mm. Within one run, each part was cut out and the associative numbers that identified the plates and joints were marked on them (Fig. 6.1.32). The total cutting time was about forty-eight hours (Fig. 6.1.33). Despite the frequent maintenance of the machine, its performance gradually decreased and in the later stages it took longer to cut the sheets (Fig. 6.1.34). As opposed to the relatively quick fabrication process, the assembly was labour intensive and time consuming, and unexpectedly required scaffolding. A number of pieces were broken or lost, and the only way to replace them was to fabricate them again. It took fifty hours for three people to assemble the parts.

Figure 6.1.30. Each discrete plate in the three-dimensional form is numbered automatically. These numbers are also assigned to parts as the parts are nested on a plane for digital fabrication.

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140. Reported from our time analysis for each material.
141. This is because the Masonite dust covered the lenses and because the laser beam lost power over time, especially if one cut for a long period without letting the machine rest.
Figure 6.1.31. Two-dimensional drawings of parts (joints and plates) automatically generated by the algorithm. These represent the geometric information about the building parts that is sent to a CNC two-axis fabrication machine.
Figure 6.1.32. This image shows the geometry of the joints and plates. The parts were nested in an optimal way to reduce material use and consequently cost.

Figure 6.1.33. A graph presenting the total cutting time.

Figure 6.1.34. A graph showing the gradual increase in the cutting time.
Evaluation through 3D scanning of the 1:1 scale prototype

A point cloud of the built prototype, established through full-scale scanning, was created in a digital environment (Fig. 6.1.35). This model allowed an understanding of the precision of the design and finite-element models and their deviations from the built artefact (Fig. 6.1.1). Three spheres were set in the scanning site as references. The 3D scanner created a point cloud of geometric samples on the surface of the physical model. These points were then used to extrapolate the shape of the built prototype (reconstruction process). Because a single scan does not produce a complete model of the prototype, multiple scans from many different directions were required to obtain information about all sides of the built pavilion. These scans had to be brought to a common reference system (alignment process) and then merged to create a complete model. To create a usable digital model out of these data points, specialised reverse-engineering software was used. Constructing a polygonal mesh produced a relatively precise digital model. This digital model had minor differences from the physical one, since the created data points deviated by a few millimetres.

Reverse-engineering the built prototype provided the critical link between the approximated geometric model and the finite-element model. It also enabled documenting and representing the pavilion’s structural performance over a longer time, such as the changes in geometry that resulted
from the creep and relaxation of the structure. For example, based on the point-cloud model, the width, length, and height of the pavilion were 3.0 x 7.0 x 2.6 metres respectively, while the digital model in Rhino was designed to be 2.75 x 6.5 x 3.0 metres. The digitalization of the real-world pavilion was of vital importance for quality assurance. A further question was how to use this information in a generative way, beyond mere analysis. The next experiment explores the potential of the 3D scanner as a generative tool for design exploration.

6.1.6. Comparison between disparate models of the exploration

The comprehensive exploration model was created gradually in the cycles of the design-to-production process with the intention of designing a form that was realisable using the available digital fabrication tools and would perform well at the site once materialised. The designers’ intention was embedded in disparate physical and digital models that were interdependently linked to one another to drive the exploration. Below are summarised comparisons between the previously described physical and digital models presenting the significance of each for the exploration.

Comparison between CNC-physical and point-cloud models

The point cloud model did not embed any features other than vertices, which are defined by X, Y, and Z coordinates. Since the accuracy of the reassembled points in the 3D model depends on the type of 3D laser scanner, the points were reassembled with minor deviations from the external surface of the prototype. Moreover, the accuracy of the reconstructed surface depends on the technique used to reconstruct the surface, through a polygonal or triangular mesh or NURBS surfaces. The minor deviations between the point-cloud model and the physical prototype were expected. Even with these deviations, the point-cloud model served its purpose for this project.

Comparison between geometric and point-cloud models

The geometric model did not embed features beyond the geometric description of each plate and joint. It lacked additional parameters such as the sagging due to the weight of the overall structure, relaxation of the material due to exposure to humidity, and the effects of additional deformation of the panels and joints when combined together. All of these aspects affected the overall geometry.

Since the current geometric modelling software programs for design are free of physical laws, the observed deviation between point-cloud and design model was expected. However, the self-calibrating nature of the polygonal system compensated for these minor differences. When dealing with real-world materials there are imperfections, and as such there is a need for geometric tolerances that take this material divergence into account.

Comparison between simulation and point-cloud models

The finite-element model covered the information regarding the weight of the overall structure that caused the sagging. However, this model gave no information about the relaxation of the material due to exposure to humidity. A minor deviation between the finite-element and point-cloud models was observed. This was due to (1) the simplification of the finite-element model because of the software’s inability to process large numbers of non-identical geometries (e.g., the geometry of the joints was simplified when exported to finite-element model, and the plastic ties were not accounted for), and (2) the large number of parameters that exist in the physical world, such as humidity, that are not embedded in the finite-element model. Moreover, to speed the simulation, the meshing of each plate and joint was simplified and reduced.
Comparison between economy model and final cost

The economy model’s predicted cost for joint and plate material was precise, although it excluded the cost of errors, such as recutting lost or broken joints and plates. On the other hand, the cost for the unexpected scaffolding during the construction was very high and missing from the economy algorithm. The calculated cost for human resources during the fabrication phase was far below reality. This is due to cost calculation based on the time taken in the initial test of cutting one Masonite board without considering the machine’s performance when running for a long time and the minor differences in the number of pieces laid out on each Masonite sheet. As shown in Figure 6.1.36, as time passed the cutting took longer.

Comparison between initial prototypes of components and full-scale prototype

The initial prototypes of just a few cells’ aggregation (Fig. 6.1.37) helped to decide on the size of the connecting cuts in the joints and plates. However, the material behaviour of the initial and final prototypes was different between due to weight differences.
6.1.7. The independence and interdependence of physical making and digital computation

The elements and the steps involved in computing a digital form are fundamentally different from those involved in making a physical prototype, but there is a meaningful interdependency between them. For instance, computing the highly ornamented structure of the pavilion included the mathematics of the surface (based on UV), consideration of orders and series, creation of plates without thickness, marking of joints, and nesting of the plates on a digital NURBS surface. Some of these digital geometric elements were never meant to be built, but were created digitally to aid the creation of the geometric model. The double-curved surface, for example, was only used to help with the digital construction of the polygons: this surface did not exist in the physical world but supported the design process. The physical making required the use of secondary structures that embraced the polygonal components in clusters and helped with the construction. However, this was not done in this project, making assembly more difficult than it had to be. The domain of information, such as the mathematics of the surface, is not important in the physical construction but is the main working area for the theoretical space of the digital and geometric world. However, this digital data is treated differently depending on the fabrication technology. In the case of this pavilion, using a CNC laser cutter led to specific approaches to and techniques for testing the digital data relating to the surface. A two-axis CNC laser cutter is fed with data representing the X and Y axes on a plane surface; knowing this, the designers treated the digital surface by extracting UV data from it to enable the construction of the polygonal pattern. If the designers had used a CNC router or a 3D printer instead of the CNC laser cutter, the way of treating the surface and the type of physical material would have been different. This shows that the techniques and methods of digital mathematical construction are dependent on the physical material and methods of fabrication in relation to the fabrication tools. The making process in the digital world was totally different from the physical one, but the theoretical space of the digital world was influenced by the techniques determined by the fabrication tool.

6.1.8. Conclusion

This experiment was a successful vehicle for testing the capacity of digital tools, particularly algorithm, for expanding the exploration to conceptually integrate environmental, structural, fabrication, and material constraints to the computational formation process. Through the cooperation between the designers’ and algorithm, meaningful interdependencies between disparate sets of digital and physical models were created. Material and fluid behaviors were efficiently predicted in the finite-element and CFD models respectively and influenced the generation of form in the geometric model through defined variables in the algorithms of form. The integration of the geometric data directly with the data received from environmental and structural simulations at the early design stage was made possible by an algorithm that contained variables and parameters of form and algorithms that acted as translators between different data formats. The employment of algorithm in the geometric model allowed, on the one hand, exploration of the spectrum of alternative forms, and on the other hand enabled their materialisation at any time throughout the process, as it allowed for the automatic generation of the geometric data fed to CNC manufacturing tools to produce the parts.
Many decisions were made based on affordability. The constraints and affordances of the materialisation stage informed the exploration space. The constraints of the fabrication tools, budget, and short timeframe set the boundaries for material choice.

This project shows that the current digital design environments, including their techniques and technologies, do not function comprehensively, since they do not cover parameters beyond geometric formation, such as material properties, dynamic forces, and gravity. Therefore, for a project to be realisable in the physical world, there is a need for the integration of different disciplines. However, to be critical, the question is whether it is appropriate to treat the relation between computational geometry and geometrically enforced material as a faulty one, which has to be corrected by constant prototyping. Are there other ways of using the constraints of the material world and fabrication tools that would push the exploration in a more speculative direction, so that something new would emerge that was not initially intended by the designer?

In this experiment, the exploration model is built out of the three compatible models within the theoretical space of exploration: the geometric model, the two expert simulation models (including the economy model), and a complementary model within the empirical space of exploration, the CNC physical model. The synthesis of these models for exploration was done with the intention of designing and realising a complex structure. However, the question is how can one use and relate these models in an exploration so that their use goes beyond merely enabling the realization of a complex structure, and beyond merely measuring the differences and discrepancies that exist between the actual physical world and the digital world, to leading to the generation of the design idea itself?

What does the designer need to integrate into a design exploration model to make informed decisions? In other words, what is the relevant information the designer needs to add to a design exploration model? If the design team had had all of the data, would the design have emerged automatically? Probably not; even with this information added, a designer is needed to make the right choices, because data will still not produce a design by itself. Is it possible to introduce too much information—is there a point at which it is disruptive, either because it is too much for the machine or because it interferes with the creative process? Too much information can be computationally too heavy and intellectually too challenging, and that may disturb the creative process.

Finally, this experiment presents scale prototyping as a necessary step not only to evaluate the digital design and ensure continuity through the interpretation, translation, and fabrication, but also as a vehicle for the creative process.
Figure 6.2.1. An installation and exhibition of the 1:1-scale physical prototype of a portion of the strip pavilion at LTU library, Lulea, Sweden. Photograph by Pooya Vahdati.
6.2. Experiment 2 (Strip):
Extended circular and uniform exploration model

Figure 6.2.2. An earlier 1:1-scale physical prototype of the pavilion during the off-site construction process: prefabrication, manufacturing, and construction of the curved parts. Photograph by Pooya Vahdati.
6.2.1. Introduction

In Experiment 1, the exploration was initiated by means of CAD models. This limited it to the geometric language afforded by the CAD software, meaning that the conception-to-production cycle was isolated by the immediate geometric affordance of CAD and was protected from outside influences. Experiment 2 aims at overcoming the immediate impact of geometry on the early exploration by introducing a physical model at the beginning of the digital cycle (Fig. 6.2.3). By selecting the physical modelling material with respect to the construction material and fabrication constraints of the full-scale counterpart, it is possible to limit the exploration to realisable (buildable) forms. This method can be an alternative to imposing geometric language at the early exploration stage.

Beginning with physical model making can be a way to bypass the immediate influence of the geometric language offered by CAD software in the early conceptualisation stages, and to use direct and intuitive interactions with physical modelling materials to explore form. For example, Dennis Sheldon describes Frank Gehry’s design process as one in which “physical model making is the principal design tool. This primacy of the construction of physical objects as the vehicle for design explorations in itself propels the firm’s work beyond the constraints of the Euclidean rationale” (Shelden 2002, 26). However, the use of physical models as part of the exploration is only meaningful when they are developed in relation to the project framework (e.g., the constraints of constructability) and in relation to the other models involved in the exploration. Shelden points out that “viewed in isolation, the operations of physical modelling are insufficient to guarantee the constructability of the full scale products that models are intended to represent. However, in Gehry’s process, models serve not simply to describe the object in scale. Rather, the processes and materials of model making are brought into alignment with, and stand in for, those of craftsmen and fabricators on the resulting building construction” (Shelden 2002, 26).

At some point the physical models have to be described digitally and geometrically in order for the form to be realised. In the case of first-generation architects such as Gehry, the designers themselves did not have computational expertise and were not engaged fully in computational techniques. They had to rely on the expertise of others, who were brought onto projects to enable the intentions of the designers. While Gehry’s process is to construct physical models initially and then use digital tools to digitise them and post-rationalise the formal intention, the subsequent development of the digital model is never fed back into physical models: the physical models are not really part of the digital continuum cycle. This means that design intentions are fixed at a very early stage and less informed by the design process. This can be seen as the post-rationalisation of the designer’s formal intention, which was manifested in physical models.

In contrast, since the new generation designers themselves have computational expertise and are engaged fully in computational design and fabrication techniques, there is an opportunity to redefine the way of using of manual physical models for conceptualisation of design as well as in relation to the overall exploration model. This experiment investigates this new opportunity. Building upon the previous experiment, the project framework of this experiment was defined to allow production with sheet material only, and the use of only a two-axis CNC milling machine or laser cutter for fabrication. Students were asked to begin the exploration with material exploration, respecting the physical modelling material and observing what it suggested, rather than impose their formal intention on it.
6.2.2. Paper strips as a starting proposition for design

Because of its flexibility and tangibility, a strip of paper is a natural choice for model making in a design exploration of curvilinear forms (Fig. 6.2.4). The fact that a strip of paper is cut from a kind of sheet material ensures that any form made from it is reproducible using another sheet material when scaling up the project. However, this scale amplification must consider the stiffness of replacement sheet material: a paper strip twists more than a plywood strip, for example.

On the other hand, the geometry of a manipulated strip of paper can be seen as a physical representation of a family of ruled surfaces called developable surfaces. Developable surfaces are a special type of ruled surface: for “each ruling there is a plane tangent to the surface along the entire ruling” (Pottmann et al. 2007, 535). In other words, they are “single-curved” and only bend, twist, or extend in one direction at a time. The most important characteristic of these geometric surfaces is that they can be flattened onto a plane without stretching, compressing, or overlapping any part of them—examples include the cylinder and the cone. Due to their property of being buildable from sheet material, developable surfaces are commonly used in industry for rationalising double-curved surfaces. For instance, developable surfaces are commonly used in designing the products...
of the auto, aerodynamics, shoe-making, and garment industries, which are often double-curved.

6.2.3. Requirement diagram

In this experiment, the paper strip was immediately used to investigate program requirements in relation to the morphological properties of the strip. This investigation was a diagrammatic one. By spiralling, twisting, flipping, and bending the paper strip in various directions, the designers tested its potential to satisfy programmatic requirements (sitting, leaning, gathering, and enclosure possibilities). The designers asked themselves what kind of figure would suit a function. They also asked what kind of usability a given figure (e.g., extension-like, flexion-like, or torsion-like features) might suggest. The paper models were then documented digitally and used as material for constructing requirement diagrams—diagrams of circulation, user interaction (e.g., sitting, leaning), social and individual space, and inside and outside spaces (Fig. 6.2.5).

6.2.4. Formal diagrams

Josef Albers said that “all art starts with a material, and therefore we have first to investigate what our material can do. So, at the beginning we will experiment without aiming at making a product. . . . Our studies should lead to constructive thinking. . . . I want you to respect the material and use it in a way that makes sense—preserve its inherent characteristics. If you can do without tools like knives and scissors, and without glue, [all] the better” (Saletnik and Schuldenfrei 2013, 93). The morphological study of the paper strip was a study of material behaviour in relation to manipulative acts. The exploration began with direct and tangible sculpting of the paper strip.

The strip was manipulated intuitively and it reacted differently to different manipulative acts. Here, the visual and tactile qualities of each manipulated strip influenced the designers’ thoughts and imagination—much like finding a friendly dialogue between the strip of paper and the form that it took, in such a way that every figure expressed something of its material character.

The paper strip carried within it potential avenues of exploration such as flexion, torsion, spiralling, twisting, bending, and folding, while precluding others, such as wrinkling. Through twisting, spiralling, flipping, and bending by hand, the paper strip was transformed to take on tangible forms, and then was fixed to a foamcore base with pins. Though a visual study method, formal figures that foreshadowed or suggested functional consequences of the requirement diagram were extracted and documented through drawings and photographs (Fig. 6.2.6).
6.2.5. Formal behaviour and performance of construction materials

If the designer is intent on a formal behaviour and decides to propagate it to the full-scale counterpart, either a construction material must be found that can assume a similar form to what paper does, or construction details that can be produced by available fabrication methods and construction materials must be designed.

In this experiment, formal figures were further investigated using other sheet materials similar to the actual construction material. Strips were made from thin plywood and aluminium sheets, and these strips were manipulated rigorously, using a diagram of formal figures and a list of manipulations as guides. Each material demonstrated different degrees of in-plane stiffness and bending resistance in taking the form of the figures, and each reacted differently to the manipulative acts. Even though the strips of different materials reacted differently in relation to their internal structure, there were similarities in their formal expression—continuity, for example—and they both prevented avenues such as wrinkling.  

6.2.6. Computational geometric model

To scale up the project and explore form with respect to the construction material and fabrication constraints, a computational geometrical model had to be created. This enabled integral formation and materialisation and provided the geometric specifications necessary for manufacturing the strips from sheet construction material. On the way to reconstructing the geometry of the paper strips digitally, parametrically, and geometrically, the designers looked for a way that would allow them to interact easily with the reconstructed geometry and ensure that the physical exploration would not end.

This was achieved through following steps:

145. Usually huge presses are used to form sheet metal to any shape needed.

146. Sculpting as a way of form development has often been used by Gehry to drive the design process of large buildings. In his practice, he usually establishes the form and then employs computational experts to translate it into developable or buildable components. This is the post-rationalisation of form, which one may call both post-rationalising and post-materialisation.

147. All of the forms under exploration were developable and buildable from sheet material. This is because all of the materials initially used for transformation were in sheet format.

148. That is, so that designing could continue even when shifted into the virtual world. On the way to computationally reconstructing the strip of paper digitally using developable surfaces, the designers sought a method that would allow interactive construction and modification and easy control over the underlying surface. The process of the interactive reconstruction of the paper strip was broken down into two parallel phases, extractive and generative.
(1) searching for a geometric concept that could be applied to the paper strip—i.e., a developable surface;

(2) capturing the form of the manipulated strip of paper digitally;

(3) searching for an algorithm to generate a developable surface from any given spatial-parameterised curve;

(4) extracting the edge curve from a digitalised physical strip, and then using it as input to the general algorithm to regenerate the form of the paper strip.

Developable surface to represent the paper strip

At a certain point the physical models had to be described geometrically. A benefit of using a strip of paper as a material for design exploration—besides it being a tangible and intuitive design tool—is that it always generates or represents a developable surface. Originating from differential geometry, developable surfaces, as mentioned above, are a special type of ruled surface. A ruled surface “contains a continuous family of straight lines called generators or rulings” (Pottmann et al. 2007, 311). Any ruled surface can be generated or represented by moving a line through space (Pottmann et al. 2007, 311). Helmut Pottmann presents two ways of generating ruled surfaces: by moving in a straight line along the directrix curve, or by connecting corresponding points of two generating curves (an example is generating a one-sheet rotational hyperboloid by connecting lines between points on two circles that are not on the same plane) (Pottmann et al. 2007, 314–315).

While ruled surfaces can be doubly or singly curved, developable surfaces are only singly curved. Developable surfaces are a special case where the surface normal at all points along a given ruling is constant (Rose 2005, 6) (Fig. 6.2.7). An equivalent definition is that developable surfaces are special ruled surfaces where for each ruling there is a plane tangent to the surface along the entire ruling (Pottmann et al. 2007, 311).

Figure 6.2.7. This image illustrates the normal vectors of a developable (a) and warped ruled surfaces (b) to show that not all ruled surfaces are developable. “A ruled surface which is not developable has normal variation along its rulings and is thus called a warped ruled surface” (Rose 2005, 7). In “(a), the normals are constant along the specified ruling while in (b), the normals vary along the ruling” (Rose 2005, 7). The figure is reproduced from “Modelling Developable Surfaces from Arbitrary Boundary Curves” a master’s thesis book by Kenneth Lloyd Patrick Rose, University of Waterloo, 2005, p. 7.
In his dissertation, Dennis Shelden identifies four recognised developable surface forms.152

1. Planar surfaces,
2. Cylindrical surfaces, where the generatrix is always parallel over the surface,
3. Conic surfaces, where the generatrix passes through a common point,
4. Tangent developable surfaces, described by the tangent sector of the space curvature at each point. (Shelden 2002, 177)

He then notes that “theoretically any developable surface may be composed into sections from one of these four classes” (Shelden 2002, 177). Thus, it is possible to say that the geometry of the strip of paper in this exploration is a segment of one or more of the surface forms classified above. To move from physical modelling to digital-computational modelling, the geometric concept was applied to the paper form. Since the paper strip was manipulated into different forms, it was not possible to assign a single form of developable surface to a whole topological area. In this case the process of geometrisation was broken down in a conical way into pieces that each have an available type of developable surface (Fig. 6.2.8).

149. One could say that another benefit of using a strip of paper as a material for design exploration is its inherent property of being a direct physical representation of developable surfaces. Note that every developable surface is a ruled surface, but the inverse of this statement is not true. Indeed, most ruled surfaces are not developable (an example is a hyperboloid surface). A ruled surface that has normal variation along its ruling is not developable and, and such surfaces are referred to as “warped ruled surfaces.” See Helmut Pottmann, Andreas Asperl, Michael Hofer, and Axel Kilian, Architectural Geometry (Pennsylvania: Bentley Institute Press, 2007), Chapter 9, pp. 311–323; Chapter 14; Chapter 15, pp. 535–561.

150. For example, hyperbolic paraboloid and one-sheet hyperboloid surfaces are double-curved ruled surfaces and thus not developable.

151. This is because the tangent plane at any point can be described by the surface normal at that point (Rose et al. 2007, 164). Mårten Nettelbladt also gives a good description of developable surface. See Nettelbladt, Mårten. (2001). “Seismological Observatory,” Diploma project at the School of Architecture, KTH, Stockholm, October 2001. It is accessible through his Webpage: http://www.omkrets.se/mnexjobb/english.htm#.

152. Note that while in his dissertation Dennis Shelden identifies four recognised developable surface forms, in Architectural Geometry Pottman, Asperl, Hofer, and Kilian categorise the developed surfaces into three basic types: cylinders, cones, and tangent surfaces of spatial curves (Pottman et al., 2007).
Input device for capturing paper strip forms

Merely finding a geometric representation for the physical model does not ensure that the physical exploration will be directly influential as the exploration evolves from physical to digital operations. For the physical exploration to be influential throughout, it must be directly linked to the digital continuum cycle. If it is left in isolation, the operations of physical modelling will not influence the exploration once it enters into digital-computational operation.

In this experiment the outermost layer of the paper strip was represented digitally as a point cloud, using three-dimensional scanning techniques to reverse-engineer it. The part of the physical model that was selected for full-scale prototyping and further exploration was scanned, and as the 3D scanner was moved over its surface, points were created at corresponding locations in the Euclidian three-dimensional space, producing a digital counterpart of the physical model in the form of a point cloud. The point cloud provided templates for extracting spatial curves, which were later parameterised (parameters were assigned to the curves) to allow modification (Fig. 6.2.9).

By creating this link, it was possible to digitally extract a new set of spatial curves that corresponded to the form of the strip for every alteration of the physical model (Fig. 6.2.9). The curve was then input to an algorithm that generated the developable surface as a counterpart representation of the actual strip of paper (Fig. 6.2.10). This enabled live alteration of the digital strip when the paper strip was altered in the real world.
The search for developable-surface algorithms

An algorithm was designed that would compute a developable surface from a parameterised spatial curve. Reducing the design input to a parameterised spatial curve maximized control over the underlying surface, allowing intuitive interaction with it and enabling an approximate regeneration of the physical strip. The designers used a method proposed by Zhao and Wang (2008) to develop an algorithm that would generate a developable surface from the parameterised curve.\textsuperscript{153} The algorithm was built from two main parts: one treated the input curve (derived from digitalising the physical paper strip) as a geodesic curve on the strip surface, and the other constructed a developable surface from the given curve as geodesic using an algorithm provided by Guo-Jin Wang, Kai Tang, and Chiew-Lan Tai (2004).

6.2.7. Integral formation and materialisation

As a developable surface that enabled its materialization from sheet material, the digitally generated strip conformed to the fabrication capacity of the construction material; however, it did not exhibit any affinity with its material character and behaviour. In other words, because it was immaterial, scaleless, and not subject to real-world forces, it did not have the same performance as an actual strip of material.

On the way towards designing the algorithm to compute the form of the strip digitally, material behaviour was simulated in the digital model. Materials bend and twist to different degrees—for instance, paper bends more than plywood. Thus a range of controlling parameters was added to the strip's algorithm and allowed the design team to control these two parameters for any given input. If a given surface exceeded the material's bending range, an error message occurred. The range was fed back from material testing into the range domain.

From fold to lamination: creating and building forms for lamination

A common way of forming metal or wood strips into a desired shape in full-scale production is to cut the geometry of the strip from a flat sheet of material and then bend it into the desired shape. A metal strip can be formed using role-forming technology, while forming a strip of wood is usually done by steaming (heat and humidity make the wood flexible for bending) or lamination (manufacturing a material in multiple layers).\textsuperscript{154} The tight budget and available fabrication tools led to the choices of wood and lamination for the full-scale production.

\textsuperscript{153} As mentioned in Chapter 3, there are different ways of constructing the geometry of a manipulated paper strip computationally. Rose et al., developed an algorithm for computing a developable surface through boundary curves; see Kenneth Rose, Alla Sheffer, Jamie Wither, Marie-Paule Cani, and Boris Thibert, “Developable Surfaces from Arbitrary Sketched Boundaries,” in Proceedings of the Fifth Eurographics Symposium on Geometry Processing, Barcelona, Spain, 2007, 163–172.

\textsuperscript{154} It is similar to wet-folding—dampening a wood sheet to manipulate the geometry—but when it is dried it retains its form.
In full-scale production, surface geometry that was initially assumed by a paper strip had to be materialised from Masonite sheets. The shift in material and scale introduced new problems and constraints into the design process that led to introduction of lamination, segmentation, and, consequently, joining. The initial strip was too long and could not be produced in one piece. To explore the lamination of Masonite components through a joint system, the following questions were asked:

- **Lamination:** how many layers are required for the structure to hold its form and allow user interaction while remaining as light as possible?

- **Segments:** How many segments should the strip be divided into? What is the maximum length of segment that would meet our fabrication and transportation constraints, such as the size of the laser bed? Where should the segments be joined so that their composition as a strip is strong enough, and where should the segments end so that the joints are not exposed to excessive loads?

- **Joints:** what kind of joint will make the assembled strip stable and strong?

Forms were designed and built to laminate the Masonite sheets. The forms were constructed from individual CNC-machined Masonite parts, which were cut to have finger joints interlock in a waffle-grid fashion. The material and production constraints (two-axis CNC laser cutting) introduced the waffle-gridding of the formwork structure (Fig. 6.2.11).

Figure 6.2.11. Right: axonometric drawing of the mould that was used to form the strip components. Left: shaping strip components on the form at a small scale.
The computed developable surface was used to shape the concave bed of the formwork (Fig. 6.2.12). A parametric algorithm was developed to compute the geometry of the convex bed of formworks corresponding to segments of the developable surface strip. The input needed for the algorithm to generate the formworks was reduced to a developable surface. This algorithm was developed in a way that would generate the formwork automatically from any given developable surface. In this model, the normal of the surface was used as a guide to position the components of the formwork perpendicular to a given surface or aligned with the plane of the surface normal (Fig. 6.2.12). The geometry of the parts was then laid on a plane and laser cut from Masonite sheets, and then assembled to test the lamination idea.

Figure 6.2.12. These figures show the steps in generating the formwork from a given developable surface. First, perpendicular planes to surface are created (a) and the rest of the formwork components are built upon these planes. Based on the feedback received from structural analyses, a strip will be split into number of parts; for each part, a formwork can be generated automatically (c).

(a) Perpendicular planes to a given developable surface. The planes are aligned with the normal vectors of the developable surface.

(b) The developable surface was used as a guide to position the components of the formwork perpendicular to the surface.

(c) Automatic generation of the formwork from a given developable surface. In this alternative, six formworks are generated to create the strip in laminated Masonite.

155. Initially the designers asked the following questions: Lamination—how many layers should there be? Segments—how many and where? Joints—what kind of joints? However, these questions were not very helpful: they were relevant and overlapping as a result of scaling the project, but they did not correlate to each other and hence were not helpful in the decision-making process. As a result, the designers reformulated the questions to correlate to each other.
The common ways to assemble a laminate permanently are heat, pressure, welding, and adhesives; the designers chose adhesives and pressure. For the thin sheets of Masonite to conform to the shape needed, they had to be pressed evenly across the surface of the strip. Heavy clamps and ratcheting straps that would apply considerable pressure were needed. A better result was achieved when the forces were applied evenly from side to side (Fig. 6.2.13).

Lamination, bending, and understanding Masonite’s capacities were essential to learning the geometrical intricacies of the form in relation to material properties. The constraints of building the form were fed back to the physical model and the algorithm of the developable surface, leading to the reconfiguration of the physical model with respect to the capacity of Masonite to conform to the geometry (Fig. 6.2.14). Experimentally, several curvatures of bending were applied to the Masonite to experience the deformation of the material required to create a potential form for the full-scale prototype. Lessons from this detail prototyping were fed back into our computational geometrical model.

Physical prototyping of details was used directly to design and test the joints (Fig. 6.2.15). Different joint outlines (e.g., finger joint, lap joint) were drawn on the laminated components, at which the laminated strip was cut apart. Subsequently, they were reconnected to test the strength at the joint location.

Figure 6.2.13. Lamination of the curved components using clamps and ratcheting straps to apply considerable pressure evenly across the lamination.
In the hyperbolic project, the geometric surface property *diagrid* ensured structural stability. In the case of the strip, the geometric property *generator line* only correlated the design to construction: the surface pattern of strip was not structurally infarmable. Structural stability in this case was achieved by the overall form of the strip and its composition. The overall form had to stand up and not tilt when forces were applied to it.

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Figure 6.2.16. The CAD-geometric model is informed by two structural analyses in a generative way: one that generates the overall geometry of form using the dynamic relaxation method, and one that generates the splitting positions on the continual strip in order to create components that can be built given the constraints of fabrication. The later analytical model ensures that the strip is not split in a crucial moment where there is extreme dead load or parts that are highly impacted by external forces, so that the intersections of the components are strong enough to allow the structure to stand.
Direct feedback: generating the geometry of the overall form (dynamic relaxation)

Direct link

Structural analysis model

Direct link

Structural analysis model
Comprehensive physical prototype
A portion of the paper model was selected and a full-scale comprehensive prototype was built to test the feasibility of the project and comprehensively assess the performance of the strip's composition (Figs. 6.2.17 and 6.2.18). Obviously, once the full-scale prototype was built, many issues were revealed that had to be fed back into the design loop. The material's behaviour changed radically as the scale changed, and new elements were needed to strengthen the joints, as tolerances between the joints and laminated layers did not accurately match those of the digital analytical model. When it came to the full-scale prototype, the designers failed to create the joints accurately.

Figure 6.2.17. Lamination of Masonite strip components for full-scale comprehensive prototyping. From left to right, adding glue on each Masonite sheet for lamination, positioning the Masonite sheets on top of each other, and using a fixed screw-on mould and accurate circular holes in each sheet for precision, to make sure each sheet is positioned exactly. Once the sheets are laid on each top of each other, considerable pressure is applied to them using straps.

Figure 6.2.18. Joining the components and assembling the comprehensive physical prototype. The structure is built from nine laminated Masonite components.
6.2.8. Algorithms between manipulating paper and laminating Masonite

At some point the physical model has to be digitally and geometrically described in order for it to be realised. As Dennis Shelden has said, “once you want to get things into a digital world you have to pick a set of algorithms. . . . The selection of each algorithm leads to completely different representations, completely different means of building and completely different economics and completely different resulting form” (Shelden 2014b). In this experiment, the challenge was to choose an algorithm that would generate the developable surfaces’ forms—representing the forms assumed by the paper strip—for every manipulation of the paper strip with input received from manual exploration and also allow the designers to build on it so that it incorporated construction concerns into the exploration. The algorithm generalized the paper strip while simultaneously specifying a way of regenerating it digitally based on constructability requirements. This line of employment is the use of algorithm for a specific design problem: it is a search for its potential to represent the design problem or question at hand parametrically, digitally, and generatively. The designers found a correlation between the design problem and the existing models in their different properties, such as the geometric and the mathematical. This requires knowledge in disciplines outside of the conventional core of design practice.

The manipulation of the paper strip entailed a different making process than the lamination of the wood strips employed in the production of the large-scale prototype. The algorithm that mediated between the physical and materialization stages not only linked the early design stage with material constraints (sheet material) and fabrication by two-axis milling, but also negotiated their capabilities. The manipulation of paper strips was quite different from the lamination of wood strips. Because of the scale of making at the early stage and the properties of paper, paper had advantages for manual exploration that the construction material did not have. However, to explore and ultimately produce the same overall form with construction materials, the logic of the form had to be resolved with discrete elements that had to come together at precise angles to create the form assumed by the paper strip. Algorithm allowed the designers to encode the constraints of the Masonite construction material (its maximum curvature) into the exploration, bounding the exploration to forms that Masonite could take on. Using paper strips, the design team could twist and bend the paper and explore formal propositions while examining the constructability of the assumed form (Fig. 6.2.19).

Once the geometry of the desired curvature was scanned, the algorithm scaled the approximate possibilities, ensuring that the curvature produced would be realisable using wood strips; if not, either the physical model was altered and reworked or a different construction method for its full-scale counterpart was developed. The algorithm ensured the regeneration of the form assumed by the paper strip, and also ensured that the digitally generated forms met the constructability requirements of a large-scale prototype in dimensionally limited sheet material.
Figure 6.2.19. Using algorithm in design exploration can entail small-scale making and large-scale physical prototyping simultaneously. Here the designers benefit from a more flexible mode of design exploration. In this image, the malleability of the paper strip offers easy exploration of the overall form; at the same time, 1:1-scale physical prototyping offers feasible construction and the exploration of manufacturing potential, which can inform the design alternatives.
6.2.9. Conclusion

In this experiment, the exploration began without the constraints of a geometric rationale. This allowed a more intuitive mode of operation, and also avoided imposing the geometric language afforded by CAD software at the conceptualisation stage. The selection of modelling material in this experiment was based on the material’s capacity to take certain geometric forms that are constructible from sheet material. This allowed the designers to explore form in a way that bypassed the immediate influence of CAD geometry in the early conceptualisation stages. Materials such as paper and cloth are relatively flexible modelling materials that are easy to sculpt and are amenable to the available fabrication techniques. They can be represented geometrically and computationally through the surface concept, and by their nature they can be unfolded into a flat surface, ensuring their potential to be materialised from flat construction materials. Planar modelling material can be seen as an exploration tool that cross-correlated the domains of design, fabrication, and geometry and limited the exploration to forms that were constructible. To create a continuation of the exploration when the design moved from physical model making with the hand to the digital computation of form, a technological interface—the 3D scanner—was used to bond the two sectors of activity. The point cloud that was generated from 3D scanning the physical model provided a point of departure for the digital exploration with the closest representation of the tangible object of exploration.

Truly improvised formal exploration occurred when the strips were designed and articulated physically; once the exploration entered the digital realm, pre-formulation began through the application of algorithms and parametric association of the geometries. Once the spatial curves had been reconstructed digitally, they were fed into the generative algorithm as inputs for generating developable linear paper strips. It was the designers’ ability to exercise the material’s capacities, correlate them to the geometric concept, and find technological bonds that enabled the continuation of the physical exploration digitally.

Though making models manually was a more intuitive and less constrained means of exploration, the space of exploration was still not a neutral one. It embodied the designers’ intention through the selection of the material for modelling. This sector of activity was linked to the other models and sectors of activity in the chain of design to production in such a way that it gave feedback and constrained the exploration.

By creating circular direct informing links between the manual physical model and the other models in the exploration, the physical model can be an intuitive tool for developing the designer’s intention with respect to the constraints of later stages of the design-to-production process. Finally, attaching a supplementary manual sector of activity—making physical models by hand—to the digital continuum cycle at the beginning, which has been made possible by using digital technology and algorithms, is only meaningful when the material and ways of making are aligned with the project framework and the constraints of full-scale production. A critical question is whether the incorporation of constraints into the exploration by means of manual physical model making instead of digital computation can do more than merely delay the geometrisation and digitalisation of the designer’s formal intention.
Figure 6.3.1. Gypsum components cast from folded plastic and paper formworks.
6.3. Experiment 3 (Hypar):
Branched, incremental, and diversified exploration model

Figure 6.3.2. Concrete component cast from dynamic formwork. Photograph by Oliver Tessmann.
6.3.1. Introduction

Bringing matter and geometry together in a generative dialogue, Experiment 3 is an open-ended exploration. It begins with the interplay between a hyperbolic paraboloid surface and paper as a modelling material. The exploration moves back and forth between computational parametric description and empirical experimentation with materials (paper, gypsum, and concrete), finally arriving at the materialisation of the design from sheet material and as cast objects.

While this experiment is similar to the previous one in that it makes manual model making integral to the computation process, it radically differs from it in how the designers treat its use in the process. In this experiment the exploration is treated as drifting design problem that evolves and changes as the designers engage with the process. The designers use paper and the hyperbolic paraboloid to establish the constraints in the exploration implicitly, without having any design concept in mind. Through the open-ended interplay between these mediums, the designers discover and refine the design concept. Instead of assuming the influences and modelling them prior to the exploration, new influences are incrementally introduced as the designers engage in the exploration. The emphasis is on the mediums of design—material, geometry, and algorithm—instead of on models. This is because they are not only the representational mediums of the single models but also the means through which the designers think, see, and make.

In contrast to Experiment 2, in which manual model making and geometric computation conform to one another, in this experiment the physical model is developed independently of the CAD model and confronts it. In this productive confrontation, the exploration gives rise to significant findings from which new aesthetic expressions emerge. When mediums are heterogeneous, the designers must find a new mechanism or feature that allows a dialogue between the disparate mediums in order to proceed towards design solutions. By synergising the heterogeneous design mediums, the designers increase the possibility of arriving at new findings.

In the previous experiments, architectural features were produced in the course of the integral computational design and digital fabrication process by using feedback loops from subsequent stages. The feedback loop is not the only way to create new features, and, in contrast, in Experiment 3 it is hybridising the mediums and processes that produces architectural features. The confrontation between the two disparate design mediums that are used to establish constraints creates a combined effect greater than when constraints are immediately translated into geometric form (Fig. 6.3.3).

In this open-ended experiment a few prototypes were produced and a dynamic formwork was developed that enabled the casting of concrete objects in various shapes using a single formwork. This approach is an alternative to conventional rigid formwork systems and the formal limitations of flexible fabric formworks.
6.3.2. Hyperbolic paraboloid

A hyperbolic paraboloid is an infinite surface in three dimensions with hyperbolic and parabolic cross-sections. It is often referred to as a “saddle” surface because of its anticlastic shape—that is, its curvature in opposite directions. It can be created by reflecting a parabola about its vertex tangent and translating the rotated copy along the original one (Pottmann et al. 2007, 310). The parametric equation to describe this type of surface mathematically is \( Z = Ax^2 - By^2 \). The hyperbolic paraboloid surface is a doubly curved and doubly ruled surface; it is doubly ruled because at every point there are two distinct lines that lie on the surface.

In this experiment the term hypar is used; the term was coined by Heinrich Engel in 1967 (Demaine, Demaine, and Lubiw 1999, 92) to refer to a partial hyperbolic paraboloid shape, which is trimmed from the full infinite surface (Fig. 6.3.4). In the computational model, the surface curvature became a variable parameter while the length of its perimeter was kept constant.

Figure 6.3.4. A hyperbolic paraboloid (left) and a partial hyperbolic paraboloid shape, or Hypar (right).
6.3.3. Materialising the hypar

Some of the most obvious ways of materialising the virtual hypar are (1) tensioning a non-stretchable fabric at its four corners by pulling and fixing two of its diagonally opposite corners in the opposite direction of the other two diagonally opposite corners; (2) spanning and tensioning a string network along a frame whose shape represents the outline of the hypar surface; and (3) distributing wooden rods along a frame whose shape represents the outline of hypar surface (Fig. 6.3.5).

On the way towards materialisation, the double curvature of the hypar was correlated with the constraints of producing it from sheet material. Negotiating these opposing points of departure became the challenge of this embedded-rationale design exploration.\textsuperscript{157}

In contrast to post-rationalisation, in which the rationalisation of geometric form for fabrication and construction takes place after “the design has been fixed,” in the embedded-rationale scenario the “geometric systems and constructional logic [are] established as an integrated part of the design process” (Peters 2008, 136) and are inherent in the logic of form, and the constraints are integral to the form exploration. In such a design process, the physical and digital models become more than a representation and simulate certain behaviours as a result of the embedded logic of geometry and construction. The geometry, the hypar, already embeds the constructional logic, as it is buildable from straight construction material. The choice of paper as a material for physical modelling was made in order to incorporate the rationale of the fabrication constraints (two-axis CNC milling and laser cutting) into the manual sector of physical exploration.

Figure 6.3.5. Left to right: materialising the hypar with fabric, a string network, and wooden rods.
6.3.4. Folding: Generative interplay between hypar and material

Going back and forth between the doubly curved surface in the computational model and paper as a sheet material was facilitated by folding: a flat, square piece of paper can be transformed into a hypar through a sequence of folding procedures (Fig. 6.3.6). As folding progresses from the sides of the piece of paper to its centre, the paper buckles and takes the form of a hypar.

In contrast to fabric, paper always maintains its in-plane stiffness and does not require a cumbersome framework. Folding paper is an intuitive, controllable, generative, and fast way to explore various shapes. Similar to Kurt Kranz’s work, in this experiment the search was for “rules, principles and procedures or processes that generate changes by artistic means but lead to consistent processes that can be controlled intuitively” (Hiller 2011).

Inspired by Josef Albers’s paper folding exercises (Horowitz and Danilowitz 2006, 84-87,125), the hypar surface was materialised in paper and became a vehicle for exploring serially differentiated components. The folding procedure allowed the materialization of the parametrically computed hypar and maintained its geometric flexibility, similar to changing the distance of the parabola end points in the digital model. The designers pushed and pulled the two opposite corners of a paper hypar to generate various figures (Fig. 6.3.7).

Figure 6.3.6. Begin by folding two diagonal creases in a square sheet of paper. Fold a two-directional corrugated accordion pattern and unfold again to produce concentric squares. Fold a ridge/valley pattern, this time starting from the corner. After folding all four corners, the planar sheet automatically curves and takes the form of a hypar.

Figure 6.3.7. Differentiation of computed hypar and paper hypar.

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158. This is what the author refers to as designing an algorithm in the form of geometry for material as the computing agent to compute the possible forms. This kinetic origami physical model allows a parametric-associative exploration of the hypar form in the physical world with the constraints of the material.
6.3.5. Generating and casting shapes

To study and explore the variant figures generated by the folded paper model, casting was used to preserve every figure. This enabled the production of a whole series of components with equal perimeter lengths but different curvatures. The folded paper model, used as a vehicle for parametric exploration, became a mould for gypsum casting. This collection of components represented a whole range of possible shapes originating from one paper formwork. The folds, necessary to transform paper into a hypar, left their traces on the component (Fig. 6.3.8).

6.3.6. Simulating the folding of the paper

The folds developed to overcome the conflict between the three-dimensionality of the hypar and the planarity of the paper became a design feature. Subsequently, they were fed back into the original parametric model, which was previously driven only by the parabola and hyperbola curves. The next model iteration incorporated the concentric square creases and the ridge and valley folds of the paper model (Fig. 6.3.9). The major effort here was to design an algorithm that would generate the geometry of folds and could simulate the process of folding of the paper. The geometry of folds was represented using twisted patch surfaces to represent the twisted rectangular stripe of the paper hypar, and the folding process was simulated computationally from the inside out: a change in the central fold drove every fold outwards (Fig. 6.3.9).
6.3.7. Folding plastic sheet and casting gypsum

The second iteration of the computational hypar was unfolded and the pattern was engraved into plastic sheet material that could better withstand the liquid gypsum. The casting bed of formwork for gypsum casting was produced by folding the square plastic sheet (Fig. 6.3.10).

The plastic’s stiffness provided far less flexibility than the paper hypar during the exploration of different shapes, limiting the geometric range of the cast objects. At the same time, while the folded plastic performed well for casting gypsum, it could not withstand the hydrostatic pressure of concrete.
### 6.3.8. Computational discretisation of the fold

The earlier exploration clearly revealed the central contradiction and challenge of this experiment: the tension between the aim for flexibility during formal exploration and the need for rigidity in the formwork. The designers needed a strong material that would prevent the formwork from bulging under the load of concrete, and at the same time they required movement in the formwork to produce components of various curvatures economically. The increased demands on material strength caused by concrete led to a reconfiguration of the folded hypar. Instead of paper or plastic, the designers chose 3.0 mm MDF for the materialization of the concrete formwork to cope with the increased hydrostatic pressure of concrete.

In contrast to the paper and plastic formworks, which twisted between each ridge and valley, the poor compression and shear properties of MDF did not allow it to twist. To overcome this problem, a third computational model was developed to rationalise the fold pattern to meet the material’s capability. The twist was replaced by another diagonal fold that transformed a twisted surface into two triangles, enabling the production of the hyper formwork from untwistable sheet material (here, 3.0 mm MDF). This third computational model reflected the rationalization and simulated the additional folding (Fig. 6.3.11).

![Figure 6.3.11. Rationalising the twisted surface by translating it into two triangles.](image)

### 6.3.9. Dynamic formwork and casting the hypar with concrete

The hypar formwork could now be CNC-cut from 3.0 mm MDF with textile-reinforced tape acting as hinges (Fig. 6.3.12). Two of these folded hypars were placed in a box with a distance of 20.0 mm between them, and the concrete was cast between them. Two elevated and opposing faces of the box were cut into triangles that could move along this diagonally cut seam, causing the hypar formwork to change its shape. Thus the formwork became dynamic and allowed for the casting of different hypar-shaped concrete objects. The triangulated folds of the formwork left their traces on both sides of the cast object.
6.3.10. From folding to dynamic formwork

The mechanical system of the dynamic formwork originated with the initial material system developed for folding paper. The shift from gypsum to concrete and an increase in scale required the formwork material to be changed; consequently, the kinetic mechanism shifted from folding and twisting using paper and plastic to hinging using MDF and textile-reinforced tape (Fig. 6.3.13). Both approaches became dynamic formwork systems that challenge the repetitive notion of conventional rigid formwork systems and the formal limitations of flexible fabric formworks.

Dynamic formwork systems as they are investigated in this research rely on various mechanisms, material capacities, and kinematics that allow them to change shape. Hence, one formwork can be used to cast concrete objects of various shapes. Through folding and hinging, it was possible to produce various hypar shapes from one formwork system.

The particular characteristics of dynamic formworks distinguish them from fabric formworks. The fabric formwork is one of very few examples that rely on the self-organisation of concrete within a system of external forces—on the meeting between the material capacities of the fabric and the viscosity of the concrete. Form emerges in a process of becoming. Fabric formworks are considered flexible formworks that rely on textile under tension due to the hydrostatic pressure of concrete. A tensioned membrane deflects into a catenary curve or shell-like surface constrained by a fixed boundary (Manelius 2012, 22). Here, flexibility leads to forms of minimal energy consumption within predefined boundary conditions. However, the range of shapes is limited by single-objective optimisation. Through the use of dynamic formworks, designers can seek to enlarge the possibilities for differentiation.
6.3.11. Integrating form, formwork, and process

The integration of formwork design into the architectural design process is driven by the idea of creating and understanding material systems. A material system is a structure with spatial, loadbearing, energy storing, or energy conducting properties which are derived from the particular material it is made of and from the process it is produced with. Computational tools and techniques allow the designer to notate and instrumentalise the intricate interactions between form, material, structure, and environment in the architectural design process.

Simulating material systems within generative digital models utilises computation beyond the mere representation of formal and geometric design schemes. The function of the model shifts from the representation of objects to the abstraction of a process and the prediction of behaviour. Simulation integrated in an iterative and circular manner allows feedback to inform the design process (Hensel and Menges 2006). In this experiment, the folding of planar faces around linear hinges in the formwork was simulated in a parametric model. The digital process not only provided the necessary geometric information for manufacturing the formwork but also generated the various concrete forms. Thus the computational model provided both a tool for the exploration of concrete elements and a system to extract fabrication data and constraints from the formwork system.

6.3.12. Assembling the hypar showcase

Finally, all of the hypar components came together in an installation as a showcase (Fig. 6.3.14). The showcase of the materialised hypars invited visitors to reflect on the roles of material and material systems throughout the design process. The components were assembled on a hyperboloid wood structure (Experiment 4) that was developed as an extension of this experiment. Components were assembled according to their weight from top to bottom, in order of paper, gypsum, and concrete components.

Figure 6.3.14. The installation of the hypar showcase.
6.3.13. Conclusion

The process leading from a mathematical description to the materialisation of the hypars was composed of iterative feedback loops and shifts between digital and physical exploration. Insights gained on the way from design to production were fed back into the design and informed the process and the design intention. Designers reflect both on and through making. Every model produced, whether physical or digital, was a step towards developing the next model in the process and part of the gradual refinement of the design intention.

Throughout this process there was a conscious search for performative and aesthetic features emerging from representation, simulation, and making. Folding became a vehicle for transforming sheet material into double-curved hypars. The ornamental qualities of folding, fed back into the computational model, became operational again as hinges in a dynamic formwork system. Technical necessities and constraints became ornaments and design features. Folding was the starting point for a materially efficient dynamic formwork that enabled the casting of different shapes from one system.
Figure 6.4.1. The showcase of hypar components—paper, gypsum, and concrete components from top to bottom—was built around the staircase of KTH School of architecture in Stockholm. The elliptical hyperboloid wooden structure that holds the components together is built from twenty-two straight wooden planks.
Figure 6.4.2. Interior and top views of the elliptical hyperboloid wooden structure that was built around the staircase.
6.4.1. Introduction

Axel Kilian, citing Frei Otto’s aphorism “I do not design, I search,” states that “to search means to ask the right question and formulate the framework accordingly” (Kilian 2006, 109). In fact, the designer does not always need to know what question to ask: the search can be open-ended and have multiple possible outcomes. A question implies an answer, and knowing the right question implies finding the right answer; a search, however, can have various results and possibilities. To use Google, for example, one doesn’t have to ask the right question—one only needs a hunch about what one is looking for.

As shown in Experiment 3, the designer reads overlapping patterns in various domains, using intuition to find ways to correlate them or to find the common denominator that establishes a connection between them. The exploration can be treated as a drifting design problem, and by giving more agency to the design process and its mediums the designer may end up somewhere other than initially intended.

Experiments 1 and 2 describe hermetic cycles, a purely digital one and an extended physical-digital one. In both of these scenarios, the exploration is subject to constraints from the beginning, and productivity results from the circular feedback loops in which information from subsequent models is integrated into the geometric model. In Experiment 3, the introduction of an independent physical model delays the digitisation of constraints and creates a combinatory effect, freeing the early design process from subservience to CAD and allowing for richer possibilities when CAD is later combined with the physical models. Like Experiment 3, Experiment 4 investigates the possibility of using detached physical models to introduce pragmatic constraints in parallel with the digital cycle in a productive manner. It pushes for a bidirectional physical and digital design process in which neither sector of activity is necessarily subservient to the other. It differs from Experiment 3 in that there the model was cross-referenced with the digital fabrication process of the full-scale counterpart, whereas here the physical modelling material is cross-referenced with both the constraints of the fabrication process and the structural behaviour of future construction materials (Fig. 6.4.3).

![Figure 6.4.3](image-url)
Design representations are meaningful and become generative when they correspond to each other. It is not enough to find a design solution by merely overlapping the worlds of geometry, physical modelling material, algorithms, and tools: these worlds should correspond to each other. When models and mediums are part of the exploration, they suggest potentials and can incorporate constraints. However, a productive exploration and significant findings occur when known and unknown conditions are bonded. As such, in order to be productive this exploration expands the integral process of previous experiments to one that extends beyond the feedback loop, and uses a bidirectional link—one in which different design representations have equal influence—to augment the exploration.

Geometry can be instrumentalised as a tool to correlate multiple domains for design exploration. In Experiment 4, a hyperboloid of one sheet, which is a ruled double-curvature surface, is used to investigate this idea. The formal logic of the hyperboloid of one sheet can be correlated to the structural, formal, and constructional domains. The capacity of geometry to represent design in multiple domains is not automatically productive. To be productive, geometry has to be challenged with material and real-world problems such as fabrication, construction, and assembly.

To bring the materialised hypar components produced in Experiment 3 together as a coherent installation, a structure based on the principle of the hyperboloid of one sheet was built around a staircase at the KTH School of Architecture in Stockholm (Fig. 6.4.1). The structure consisted of twenty-two straight wooden planks with cross-sections of 2.5 by 20 centimetres.

### 6.4.2. Hyperboloid of one-sheet

A hyperboloid of one sheet is an infinite surface in three dimensions with hyperboloid cross-sections, and can be described by two sets of lines (Fig. 6.4.4). The surface can be generated by rotating a straight line, skewed to the rotational (z) axis (Pottmann et al. 2007, 297). It is a doubly ruled surface, meaning it has two sets of intersecting straight lines (g and h in Fig. 6.4.4), running across them. A hyperboloid of one-sheet is either elliptical or circular, depending on the plane sections parallel to the x-y plane. This project uses the circular hyperboloid of one-sheet known as a hyperbola of revolution.

### 6.4.3. Use of geometry to correlate multiple domains

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159. The ruled double-curvature surface is two sets of straight lines that are overlapped, creating a diagrid. Diagrid geometry suggests a stable structural system, and being made of lines it suggests construction using linear elements.

160. This is in contrast to a developable surface, which can be defined by a set of non-intersecting straight lines. The Strip project (Experiment 2) is based on the developable surface.

161. Also known as a one-sheet rotational hyperboloid, one-sheet hyperboloid, and hyperboloid of revolution. Sometimes described as an elliptical hyperboloid, it has ellipses for plane sections parallel to the x-y plane. When $a = b$ in the equation $X^2/A^2 + Y^2/B^2 - Z^2/C^2 = 1$, the elliptical hyperboloid of one-sheet becomes the hyperbola of revolution and the traces parallel to the x-y plane become circles. It is a double-ruled hyperboloid surface.
On the way to bringing the materialised hypar components that were produced in Experiment 4 together as a coherent installation, the designers found that the form of a hypar interacts with the hyperboloid of one-sheet surface compositionally and sympathizes with it. The hyperboloid of one-sheet had been frequently used in the construction of lattice towers. A great example and its first application in architecture as a built structure was Shukhov Tower in Polibino by engineer Vladimir G. Shukhov.

The overall form of the hyperboloid surface together with its property of being doubly ruled—the existence of two sets of intersecting lines across the surface—make it both a structurally stable and constructionally conventional form. The intersecting lines across the surface create a diagrid, which, when materialized and fixed at its junctions, results in a structurally stable form. These straight lines can also be interpreted and translated as linear building elements, for example as straight beams. Because of the logic of its form, the hyperbola of revolution’s geometry can be seen as a bond that enables the designer to correlate multiple domains for design exploration. Correlating the design, structural, and constructional domains visually, the diagrid-lines were used in this experiment to guide the composition, structural support, and scale assembly of the hypar components into a coherent installation. In the search for composition, structural stability, and construction, a general question was asked: what are the surface conditions that are of interest at the borderline of design representations (geometry and physical modelling materials) and the actual construction material and built outcome? In light of this question, two further questions were specified: how large should a diagrid be in relation to the hypar components, and how many diagrids should be associated with each component so that they are stable enough and visually desirable while not exceeding the budget?

6.4.4. Parametric-associative system for exploration

Understanding the hyperbola of revolution and designing it from its two sets of lines (diagrid) became a design issue. Using the algorithmic tool Grasshopper, a parametric-associative model was created to represent a hyperbola of revolution by means of geometric dependency and through two sets of lines. The two sets of lines were generated by connecting the points in the two circles (C1 and C2), which were laid in parallel planes (Fig. 6.4.5). These sets of lines then generated hyperboloid surfaces.

By changing the defined parameters, variants of the overall form and surface conditions of a hyperbola of revolution could be generated. The parameters were:

R1 and R2: the radii of two circles;

P: the number of points on the circles;

H: the distance between the planes of the two circles (top and bottom planes; later in the design process, this variable was set to the height of the ceiling);

SH, C1, C2: the Shift List (SH) defines which point in Circle 1 (C1) is connected to which point in Circle 2 (C2)—connecting the corresponding points on the two circles produces a cylinder, and connecting points on the two circles that are not corresponding and are apart produces a hyperboloid with a sectional hyperbola.

Any change in the above parameters affected the derivation of the hyperboloid surface, affecting in turn the overall form (Fig. 6.4.6).
Also known as a one-sheet rotational hyperboloid, one-sheet hyperboloid, and hyperboloid of revolution. Sometimes described as an elliptical hyperboloid, it has ellipses for plane sections parallel to the x-y plane. When a = b in the equation \( X^2/A^2 + Y^2/B^2 - Z^2/C^2 = 1 \), the elliptical hyperboloid of one-sheet becomes the hyperbola of revolution and the traces parallel to the x-y plane become circles. It is a double-ruled hyperboloid surface.


Aside from the composition, the designers benefit from its representation across multiple domains of design, construction, and structure.
6.4.5. Shortcomings of the parametric-associative system

In the search for a compositional dependency between the diagrid of the surface and hypars, the initial parametric-associative model was developed further to encompass the hypar components. The hypar components were designed as part of the hierarchical dependency tree by being associated to the diagrids (Fig. 6.4.7). However, this only allowed a one-directional exploration link between the diagrid and the hypar components.

Because the current parametric-associative system developed for CAD-geometric models has a one-directional hierarchical associative parent-child relationship, it was possible to explore the changes in the hypar components by changing the values assigned to the variables of the hyperbola of revolution, but it was not possible to explore the variations of the diagrid of the hyperbola of revolution by changing the variables of the hypar components. The current parametric-associative dependency tree allows propagation of effects only from the parents towards the children (Fig. 6.4.8): changes in the child do not affect the parent.
6.4.6. Detached manual model making for bidirectional exploration

To overcome the shortcomings of the parametric-associative system, a detached manual sector of activity was developed, tightly joined with digital computation sector, to allow bidirectional exploration (Fig. 6.4.9). Axel Kilian refers to bidirectionality as the “ability to reverse the link between design representations”; he describes it as “domain-independent” and says that “it can be enhanced through computational and physical constructs. . . . By adding bidirectional properties to the translation between different design representations, design exploration can support even complex constraint dependencies” (Kilian 2006, 22).

The search for visual fitness, scale, and composition was a bidirectional iteration between the digital computation of the hyperbola of revolution and the physical computation of the paper hypar (Fig. 6.4.9). This was done by overlapping and correlating the digitally represented hyperbola of revolution surface model with the physical paper hypar model. The paper hypar model was designed to have kinetic properties with respect to its associative-parametric digital counterpart. The paper hypar was placed on the screen over the intersecting lines of the hyperbola of revolution surface. While changing the variables of the digital hyperbola of revolution surface, the angle of the hypar corner was adjusted to correspond to the degree of intersection lines. Alternately, when the angle of the paper hypar corner was changed by hand, the digital lines were adapted to it by manually changing the variables of the digital hyperbola of revolution. In bidirectional exploration either representation, the digital or the physical, can be the design driver: the two design representations alternate in the roles of driver and driven. Both of the design representations are given equal power in driving the exploration and neither representation is subservient to the other.

In this experiment, the designers who mediated between different design representations created the bidirectional link: the composition was visually assessed and new changes to the computed surface or paper hypar were made. The approximate scale of each hypar element, their composition on the structure, and the approximate angle of the structure were estimated through this quick bidirectional exploration while keeping in mind fabrication and construction constraints.

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165. This involved the designer to manually modify the digital model through the mouse and the paper hypar.

166. The driver is the one influencing and the driven is the one being influenced.
6.4.7. Incorporating the structural behaviour of materials into the exploration

The Grasshopper model (geometric dependency model) was purely geometric and not the best tool for exploring the structural system and types of forces. In search of a structural system and construction material, other detached physical models and activities were introduced into the exploration.

Possible materials for materialising the hyperbola of revolution surface through physical modelling include string, wooden dowels, and metal rods. These materials can conveniently play the role of the straight lines that the hyperbola of revolution surface consists of, but they do not exhibit the same structural behaviour. To incorporate the constraints of materiality—the fact of being made of matter and being subject to forces—into the exploration, two physical models were made: one with string and the other with wooden skewers (Fig. 6.4.10). The network of strings and the network of wooden skewers can take on the same geometric composition to assume the form of hyperbola of revolution. They both assume or project a network of lines. However, while the choice of string puts the system in tension, the choice of wooden skewers puts the system in compression.

When scaling up the project, tensioning wire and binding wooden dowels require two different construction set-ups, which would dramatically impact the direction of further design. In search of a suitable structural system and construction material, the studies from physical models were evaluated with respect to site, economy, and time constraints. The tension model was abandoned as a result of site constraints: in the tension model there was considerable force on the top and bottom circular elements, which would have required stable ring connections in the ceiling and floor, but it was not possible to drill into the concrete ceiling and tile floor. Consequently, the compression model was chosen as the structural system. The planned wooden dowels were replaced by wooden boards as a result of available material that would fit the tight budget.
The principle of the hyperboloid was often used in steel construction by Vladimir Shukhov. An example is the hyperboloid Adziogol Lighthouse of 1911 (Rosenblatt 1975).

A three-axis milling machine can only make ninety-degree cuts, as the milling arm only moves on the x, y, and z axes. Sometimes the z movement is performed by the table.

6.4.8. Persistent reformation and recreation of the CAD-geometric model as a result of incorporating fabrication and material constraints

Wooden boards were found to be a suitable construction material for the full-scale structure. In order to incorporate the constraints and potentials of wooden boards into the digital model in a generative way, the initial parametric-associative model, which consisted only of lines, was developed to incorporate the variables of the geometry of wooden boards: length, width, and thickness. To create the parametrically adjustable board profile, two ends as variables were defined and then a rectangular prism was extruded between them from one circle to the other.

Once the shapes of the board intersections were studied, it was revealed that the boards would not intersect at right angles. The angles of the intersections varied from one end of a board to the other: at the base of the structure, the boards would intersect on broad sides, and as they get closer to the ceiling they would intersect on their edges (Fig. 6.4.11).

Solely having access to a three-axis milling machine, cutting out angles on the boards was not feasible. An alternative solution was to overlap the planks rather than have them intersect. This idea was further explored through a number of physical models.

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167. The principle of the hyperboloid was often used in steel construction by Vladimir Shukhov. An example is the hyperboloid Adziogol Lighthouse of 1911 (Rosenblatt 1975).

168. A three-axis milling machine can only make ninety-degree cuts, as the milling arm only moves on the x, y, and z axes. Sometimes the z movement is performed by the table.
Overlapping soon became a serious design issue. In order to find a stable way of overlapping the boards, the designers sought a way of correlating the geometric principle and the properties of wood. By placing a board tangentially to the top and bottom circles, a face of the board would always be pointing outwards; in other words, a face of the board would always be part of an invisible hyperbola of revolution surface (Fig. 6.4.12). The farther apart the tangent points of the circles were, the more twist occurred in the boards (Fig. 6.4.13), which had to be considered. This was initially explored through a scaleless physical model and sketch in Rhino (Fig. 6.4.13). Here, the boards would twist and overlap from their width.

A new parametric-associative model was developed from the earlier line model, representing a lattice structure of wooden boards connected tangentially to the top and bottom circles. In this model, two rectangular profiles with a common variable were tangential to the ceiling and floor circles, then they were swept along the line (Fig. 6.4.14). Contrary to the previous models that took into account only the position of the boards in relation to the ground, this model was built based on the positions of the two ends of the boards at the top and bottom circles.

Parallel to computational modelling, boards with a dimension of 5 x 20 cm were purchased and their thickness ripped down to approximately 2.5 x 20 cm to increase their flexibility so that they would twist more easily. The information about the board dimensions was put into the algorithm of the computational model, from which the manufacturing file was extracted (Fig. 6.4.15). Manufacturing entailed cutting the ends of the boards according to the digital model, and making holes in each board at the intersection points which would later be used to tie the overlapping boards together. Drilling holes and using plastic ties was an alternative to nailing, as the designers wanted to avoid cracks in the planks. Because of the amount of torsion in the planks, some flexibility in the joints was necessary.
Figure 6.4.12. Rather than intersecting the top and bottom circles (left), the boards were placed tangentially (right).

Figure 6.4.13. Twisted surface from line tangent to two circles in parallel planes (left). Boards are tangential to the top and bottom circles (right).

Figure 6.4.14. Reforming the algorithm and creating a new iteration of the parametric model based on the overlapping of the wooden boards (left) and the detail of the overlapping boards (right).
Figure 6.4.15. Producing fabrication geometries for fabricating the parts of the full-scale physical model.
6.4.9. Assembly of the full-scale physical model

Unlike building the small physical models, assembling the full-scale model with wooden boards onsite was challenging. In the small physical model, pushing each wooden strip through the cardboard at top and bottom made them stable and kept them in position (Fig. 6.4.16). Obviously, one cannot push wooden boards through a concrete ceiling and floor. In the full-scale assembly, a ring was made from MDF with cuts that kept the ends of the boards in position at the ground level. Since no such ring could be connected to the ceiling to fix the other end of each board in position, a cable was threaded through the last hole in each board to hold the twelve boards in six V-shaped pairs in position. The top ends of the two boards in each V shape were fixed together with a cable tie before assembly. As the number of boards that were assembled increased, the structure held itself together.

The scaling of assembly from a small physical model to the actual site was labour intensive. Full-scale assembly required extra effort to force the wooden planks into place while holding the previously assembled planks. If the circle at the top of the structure was larger than the one at the bottom, the tendency was for the top to droop; if the top was smaller than the bottom, the forces were directed to the bottom of the structure, which, when the components were added, would have become too heavy. The first option was preferred.

To create the opening that would provide access to the staircase, additional wooden planks were added to reinforce the intended opening. Then the boards at the intended opening were cut out of the main structure. The boards did not jump out of place (Fig. 6.4.17): once a board was in place it did not tend to move out of position.

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169. Tension was only in the rings, so technically just a wire could have used for both the top and bottom rings. However, as the structure included a traffic path for walkers, the use of wire at the ground level was not feasible.
The placement of the different types of previously produced hypars—paper, gypsum, and concrete—in the structure was dependant on their weight and the diagram that was developed during the design process: the type of hypar component at each level of the structure was determined based on the weight of the components. Paper was placed at the top, gypsum in the middle, and concrete at the bottom of the structure.

The connections between the components and the main structure were resolved during the folding and casting of the components at an early design stage. Knots and cable ties were used at the three corners of the paper components. During the casting of the concrete and gypsum components, the reinforcement fabric and chicken wire were left exposed along the two edges of the components (Fig. 6.4.18). The gypsum was connected to the structure by stapling the fabric along its edge to the wooden planks, and the concrete components were connected to the structure by stapling the exposed chicken wire.

6.4.10. Conclusion

The parametric-associative system currently in use has shortcomings that limit the exploration to a one-directional propagation of effects according to changes in a parent’s variables. Therefore, using only digital tools and their affiliated algorithmic techniques limits the exploration to a one-directional effect of constraints. To enhance the exploration, independent physical models were introduced that worked together with the digital one in a bidirectional manner.

What if the parametric-associative system in the algorithmic tools were improved to allow the switching of the driver after the creation of the associative tree structures, enabling the designer to reassign the driver and change the sources and direction of influence (Fig. 6.4.19)?

The key benefit of introducing detached physical models to work together with the digital cycle was the enabling of a complex exploration and multiple levels of design drivers. However, these models were not really linked and did not affect each other directly, only affecting each other through the agency of the designer. In the future, perhaps the parametric-associative system in the algorithmic tools could be designed to enable the designer to reassign the driver. Perhaps in such a scenario, it would also be possible to inform the diagrid by directly interacting with the digital model through the
Figure 6.4.18. Chicken wire (left) and reinforcement fabric (right) were left exposed along the edges of the components.

Figure 6.4.19. The image on the left shows the current one-directional propagation of effects from parents to children. The figure at right suggests the further development of tools for allowing the designer to reassign the driver and change the direction of influence in the tree structure.

Figure 6.4.20. Envisioning the possibility of an automated link between the physical model and digital parametric-associative model.
physical model using the screen (Fig. 6.4.20), similar to the touch-screen and stylus-driven devices in smartphones, which allow the user to control and provide data to the computer using physical gestures.

Geometry was used as a tool to correlate multiple domains within an exploration by means of its formal logic. However, it is still an immaterial and scaleless design tool. In this experiment the use of a CAE expert model as a generative tool for exploring forces in the exploration would not have been very useful, because the construction material was not predetermined. Instead, the employment of independent physical models aided in determining the type of construction material as well as revealing construction strategies. For instance, when tensioning the strings in the string network model, the designers were made aware of the construction requirements of the model, such as the need for a wooden framework for tensioning the string; similarly, when binding the wooden skewers with rubber bands, the designers were made aware of the overlapping nodes, which brought up issues such as whether to use joints, an interlocking system, or overlapping.

As discussed in the introduction to this experiment, design representations become meaningful and generative when they correspond to each other; it is not enough to find a design solution merely by overlapping the worlds of algorithm, geometry, matter, and form—these worlds should correspond, confront and challenge to each other. As shown above, strings, wooden dowels, and lines overlap but do not necessarily correspond to one another. A diagrid geometry suggests a stable structural system, and consisting only of lines it suggests construction using linear material. However, there are more significant details in the act of actual construction and assembly that were never part of the geometry and algorithm of the digital environment.

Maybe a more cohesive relation between design and construction, between designer and design and fabrication tools, between designer and models, and between models and mediums is possible. By creating feedback loops, selecting modelling materials, and selecting certain geometric concepts, we can now limit the design process to what is buildable, rather than explore everything that can be imagined outside of material constraints. At the same time, the possibilities for building are brought nearer to the possibilities of the imagination by tools that enable the employment of simulation in a generative manner—models that incorporate predicted material and structural behaviour into form generation.

It is common that one tries to improve not only the object of an exploration, but the exploration itself. In doing so the designer may find that the available tools are not good enough and realise that a better tool is needed. The designer realises this only by doing, and by pushing the limits of what the tools are capable of.

In this experiment the “better” design tool was the combination of digital and physical models—that is to say it was not a case of introducing a new and better tool, but of realising that earlier tools do not necessarily become obsolete as new ones are developed. Because they both are capable of incorporating information into the exploration but do so differently, the designer may want to keep both. Then comes the question of how these old and new tools can communicate in a productive manner. Just as the mouse did not make the keyboard obsolete, algorithm-based design and digital fabrication have made neither the designer nor physical modelling obsolete. The designer is still needed, and the designer in turn still needs the old tools, despite the introduction of new ones.
A stylus is a pen-like instrument that is used to input commands to a computer screen.
Conclusion and Reflections
This study set out to investigate the use of computation and digital fabrication for design exploration in the context of architecture as material practice. It recognised their potential for allowing the designer to explore form integrally with its materialisation and questioned their potential for enabling creative exploration in such a trajectory. It looked at how multiple constraints can be incorporated into the design exploration, and how computation can be used in such a way that the exploration is specific enough to be constrained by materiality and at the same time sufficiently flexible to allow creativity, increasing the potential for arriving at significant invention and aiding the designer in ideation.

The thesis identifies algorithms and algorithmic thinking as a basis for practicing computation in design exploration. Speculating that formalising designs solely by means of algorithm—that is, through formal logic—limits the creative exploration and reduces the potential for significant invention, the study also investigates whether diversifying the mediums used to incorporate constraints increases the potential for significant invention. In this research, such diversification was achieved by incorporating constraints using geometry and material in synergy with algorithm. This revealed algorithm’s potential as a generative design tool that allows the designer to diversify and expand the design exploration by linking disparate sets of models to one another. These links in turn enable the designer to examine new interdependencies and gain new insight. The following sections summarise and reflect on the key findings of the experiments conducted as the practical component of this research. These experiments were carried out in order to answer the following research questions, which provided the framework for this research:

How can computation and digital fabrication be used in the design exploration to aid ideation and foster significant discovery, while at the same time engaging the designer’s different domains of activity, thinking, seeing, and making?

In particular, does diversifying the mediums used to incorporate constraints into an exploration improve ideation and foster significant discovery?

What is the new exploration model that is enabled by computation, and what is the role of the designer in it?

7.1. Synthesis of the key findings

The main empirical findings resulted from the experiments, and were summarised in the chapter on the exploration model. This section will synthesise those findings with the theoretical findings in order to answer the research questions.
7.1.1. Computation and digital fabrication for design exploration

Today, computation serves as an important intermediary agent for the integration of analyses and the logic of construction into the design exploration. Computational design exploration usually involves the designer establishing constraints and making them inherent to the design exploration model, then exploring their implications in design alternatives using computation. In the context of architecture as material practice, the exploration of form is carried out with respect to material properties, structural behaviour, and environmental conditions. This has been made possible by the advances in computational technologies, which facilitate integral computation—the integration of CAD and CAE in the design process. The coupling of CAD with CNC fabrication machinery gave rise to the concept of integral computation and materialisation, in which the exploration of form computationally is integrally connected to its materialisation.

Computation in architecture is practiced by means of programming, scripting, or the graphical scripting editors available in 3D-modelling software. This involves the designer working with algorithms and the parametric-associative system. The algorithm itself becomes a design tool, a means through which the designer thinks and designs. While beneficial, algorithms and the parametric-associative system also impose certain limitations on creative exploration. The following are benefits and limitations of using algorithms and the parametric-associative system for design exploration.

Using algorithm, the designer can connect the exploration to real-world problems. As the basis for practicing computation in design, algorithm makes it possible to incorporate constraints by defining parameters in the logical description of form, and to integrate structural and climatic analyses in a generative way to generate the geometry and topology of a form.

Using algorithm, the designer can explore a broad spectrum of possible forms with respect to the real-world problems of the latter stages of design. Instead of drawing a form, the designer works out an algorithm to describe formal relations and parameters. By changing the parameters, a spectrum of possible forms can be explored.

Using algorithm to formalise design requires a considerable amount of preformulation and the “structuring [of] the design approach early on in the design process” (Kilian 2006, 54). As shown in Experiment 1, the spectrum of possible forms has to rely on the different scopes of the exploration. The scope of the exploration can be formal variations related to problem solving (e.g., ensuring the stability of the structure) or to issues of aesthetics or usability (e.g., the search for the best form for sitting and lying down that will also provide shelter), and so on. Ultimately, the exploration must deal with these in combination. Using algorithm, the designer is forced to conceptualise these scopes prior to the act of exploration. The exploration begins with the designer determining what scopes are involved in the exploration (e.g., structural requirements and wind direction), formulating the influential parameters in the CAD-geometric model, and then linking the CAD and CAE simulation models. Rick Smith criticises parametric modelling for requiring the designer to conceptualize what will be modelled in
advance. He argues that designers, in doing so, “may over constrain or find that [they] need to adjust the program or begin programming all over again because [they] have taken the wrong approach” (Smith 2007, 2).

**Using computational technology, the designer is able to create feedback loops in the exploration model and reform the initial design idea. This is done by linking the beginning and predicted end of the exploration directly in a generative way.** Kolarevic has coined the term “digital continuum,” which he defines as “a direct link from design through to construction” (Kolarevic 2003d, 7) in which an array of models is created, each connected to previous ones informatively in a circular fashion—that is, in a feedback loop. Here, computation and digital technology are used “as an enabling apparatus that directly integrates conception and production” (Kolarevic 2003d, 3). This approach to using computational technology is common in the current practice of computation and digital fabrication. While it extends the design exploration by integrating different aspects of a building project, its emphasis on creating conformity and continuity among different aspects of the design project reduces the exploration model to involvement with just building parts and isolates the exploration to the models of those concepts that were assumed by the designer prior to act of exploration. Such an approach to using computational tools reduces their role in ideation and turns them into instruments for realising a preformulated idea.

When it depends solely on computation and digital fabrication, the exploration is immediately influenced and limited by the geometric language afforded by software. This means that the exploration model is isolated by the immediate geometric affordance of CAD and is protected from outside influences. The form only evolves from the synthesis of the subsequent models in the exploration, and therefore expression of architectural form is reduced to the varying tones of only one fabrication technique and simulation at a time. This approach can turn the design exploration model into a uniform cycle of digital design to production and limit the potential for significant discovery.

The immediate outputs of algorithms are intellectual ones, such as numbers, text, and geometry. In the context of architecture as material practice, it is crucial to explore, examine, and evaluate these algorithmic outputs materially. By coupling the computation of form with digital fabrication, it is possible to evaluate design tactilely and intuitively.

The algorithm remains a rational means of design, which requires the designer to describe procedures in terms of logic. When coupling computation with digital fabrication, the author sees a tension between the descriptive nature of computation and empirical nature of materialisation. For example, for fabrication constraints to be incorporated into the exploration, the formal solutions to the problems of fabrication must be described in terms of parameters and geometric relations prior to the act of exploration. To overcome such tension at the early design stage, the incorporation of constraints into the exploration can be accomplished through the selection of modelling materials or geometric concepts whose inherent properties impose the necessary constraints.
While this dissertation supports integral computation and materialisation, the use of algorithm in design can go far beyond mere technical solutions. Rather than being used to reduce the exploration model to involvement with just the building part and limiting it to digital conformity, algorithm can be used to aid designers in ideation. Ultimately, it is the designer who identifies the constraints, formulates them, and links them to one another. Therefore, the tools at the designer’s disposal to enable this become important.

7.1.2. Establishing constraints: implicit versus explicit

Constraints can be modelled in the exploration through the parameters and variables of an algorithm by choosing a geometric concept whose properties correspond to the constraint or by choosing physical modelling materials whose capacities correspond to the constraint. The experiments reveal the difference it makes when constraints are established by means of pure logic, geometry, or material. Establishing the constraints in an exploration using an algorithm is explicit; modelling them through the choice of geometric primitives or modelling material is implicit. For example, in Experiment 1 the surface relaxation with respect to gravity and finding the form of the surface with respect to wind currents involves the designer explicitly defining the parameters and values of the influential constraints in the algorithmic definition of surface, whereas in Experiment 2 the constraint of planarity is implicit in the properties of the paper strip and the developable surface.

By choosing modelling materials or geometric concepts that have built-in constraints, it is possible to explore form intuitively and bypass immediate logical and procedural operations. Whereas computing form by means of algorithm requires the designer to preformulate the procedure and describe it in terms of algorithm prior to the act of computation and exploration, exploring form through hand manipulation of material does not necessarily follow a procedure or describe one. Rather, the designer can rely on the material to compute. An example is Experiment 2, Strip, in which engaging with a strip of paper to explore the form was a more intuitive and easier process than modifying a developable-surface algorithm. The exploration of form through a developable-surface algorithm would have required the designers to redefine the mathematical logic for the geometry of events such as twists, bends, folds, and so on prior to the act of exploration; only when these parameters were described would the designers be able to explore the variations of form by altering the parameters. By manipulating material, the designer may find unplanned events, and these discoveries can drive the designer’s intention. Since design ideas are not always clear at such an early stage, physical modelling and crafting enable the concurrent development of the design intention and the underlying design intent.

171. In a linear process the communication between models is one-way. One problem with a linear process is that early conceptualisation is typically done with no consideration of the constraints of later stages, which will come into play as design proceeds. Another problem is that the results of later stages cannot be fed back to the early models, as there is no feedback mechanism.
On the other hand, while forming a developable surface by means of digital interfaces was extremely difficult and unintuitive, unfolding the computed developable surface was easy. At the same time, exploring all the possible locations of the joints in relation to the overall form and the constraints of component size would not have been possible without the use of computation. Therefore, the manual physical model does not replace the digital one, nor the digital model the physical one. Rather, they complement one another. However, the use of manual modelling in an exploration is only meaningful if it performs a specific task in the process in the context of the design question that is being explored.

7.1.3. Integrating modes of exploration: thinking, seeing, and making

Algorithm, geometry, and material involve the designer in three domains of activity that can be categorised by the terms thinking, seeing, and making. The integration of these domains of activity is fundamental to the act of design. The embodiment of the designer’s intention and the design constraints in diverse mediums augments the designer’s experience in the exploration, which consequently impacts its outcome. The exploration model is not only about the external constraints: these constraints, once established in the exploration, are internalised in the language of the design mediums. These mediums themselves are prescriptive: their characteristics and limitations influence how the designer works with them. This in turn influences ideation in a design project and ultimately what is designed.

The combination of these mediums in an exploration is only meaningful if they are linked and perform specific tasks in the context of the design question being explored—otherwise their combination would be disconnected. By creating interdependencies between these mediums, the exploration engages the designer’s different domains of activity. As shown in the experiments, the designer can create interdependencies between algorithms, geometry, and material throughout the design exploration. In combining and synergising these mediums, there is a tension between the descriptive and intuitive aspects of an exploration. This requires the designer to interpret, translate between, and convert different design mediums and processes. Since algorithm is a rational means of design, in every shift between manual model making and generative computation the designer has to describe procedures in terms of logic. The designer plays a significant role in describing empirical experimentation and visual observation in terms of parameters and algorithms. It is in the translation between these mediums that new things emerge.

7.1.4. Computation to extend the design exploration model

This dissertation views the exploration model as a mediating artefact that aids the designer in ideation and the exploration of design alternatives. Traditionally, the exploration model created by the designer used a single model. Today, a new exploration model emerges from the integration of disparate models and mediums. This is because the designer can use computation to simulate different aspects of a building project, as well as to
facilitate communication between different kinds of models and mediums. Through the use of algorithms, an intricate network of models can be created, and these models work together even if they are only loosely linked. Such an integrated, algorithmic exploration model enables the designer to gain new insight by modelling interdependencies that help in understanding design parameters and in turn drive them in an integrated fashion.

An algorithm facilitates the linking of disparate models by acting as a translator—that is, as an interface between different information formats. It does this, for example, by sending and translating data between two disparate models. In this way, one model can be driven by the outcomes of another. The algorithmic feedback loops linking the CAD models and structural analyses in Experiments 1 and 2, in which the results from the finite element analyses automatically drive the geometry and topology in the CAD model, are examples of this.

The kinds of links created differ. Some are algorithmic, as in the example above, and some are human-assisted, meaning the link requires the mediation of the designer. The designer’s mediation can mean, for example, observing results and then acting upon them by changing parameters or concepts. Sometimes, as in Experiment 1, the links are presumed prior to beginning the exploration and are built into the overall process from the start; sometimes they are built throughout the course of the project, as in Experiments 3 and 4. This depends on whether the designer’s approach to the exploration is goal oriented or open-ended, respectively.

As illustrated in the experiments, the exploration model that is developed with the aid of computation can exceed human imagination. Each model in an exploration is simplified to incorporate a narrow range of constraints, for example structural constraints in a structural model or climatic constraints in a fluid dynamic model. Nevertheless, once these models are linked, their linkage can be so intricate as to elude human understanding. Moreover, in an algorithmic exploration model, the designer is both a part of the model and at the same time external to the model. By choosing the kinds of links and interdependencies between models, and by treating the design process in a particular way in relation to ideation, the designer plays a significant role in the exploration and impacts its trajectory. Below are types of links and approaches that were investigated in the experiments, and the exploration models that emerged from the experiments.

Circular links versus bidirectional and cross links

In an attempt to escape the limitations of linear processes, two kinds of links, circular links (feedback loops) and bidirectional links, are used in the experiments as mechanisms for interaction between the models. Engaging them produces nonlinear processes in the exploration. The two, how-

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172. Note that “a single model still contains potentially many parts” (Kilian 2015).
173. In a linear process the communication between models is one-way. One problem with a linear process is that early conceptualisation is typically done with no consideration of the constraints of later stages, which will come into play as design proceeds. Another problem is that the results of later stages cannot be fed back to the early models, as there is no feedback mechanism.
ever, must not be confused. The feedback loop is monodirectional; as such, it keeps the design exploration within a deterministic framework, while the bidirectional link does not. When a link is bidirectional, it allows the propagation of influence in two directions, but not at the same time. Put another way, the bidirectional linking of models A and B allows the exploration to produce inverse relationships: if A drives B, then B can also drive A. The advantage is that when the designer initially links two aspects of a design together, it can be done with one direction in mind, but as design proceeds and different aspects enter into a project, the designer has the option of reversing the link.

The parametric-associative system intrinsic to practicing computation goes along with a circular link easily, but this is not the case with a bidirectional one. The parametric-associative system does not allow a change in the direction of influence in the hierarchical dependencies. Therefore, the use of computation alone to enable a nonlinear design process turns the exploration model to a unidirectional cycle of design to production. Its nonlinearity relies on circular informing links, which only allow the creation of monodirectional interdependency. This reduces the potential for novel discoveries by limiting the exploration of form to the synthesis of the results of the models subsequent to the CAD model in the digital chain. Ultimately this means that the exploration of form is limited to the effects and limitations of CAD’s ability to modify its own behaviour. As shown in the first two experiments, the feedback loop allows the reformation of the CAD model at both the overall and component level. It can also give rise to significant findings, but it does so in a deterministic environment.

One way to facilitate the reversing of dependency in an exploration is to use computation in synergy with physical modelling and create a human-assisted bidirectional link. The designer mediates and creates this link by sensing and evaluating design and then manually changing the parameters of the digital or physical model. As shown in Experiment 4, in allowing a bidirectional propagation of effect through the use of physical-digital modelling, the characteristics of the physical model must be developed in such a way that it is compatible with the parametric-associative digital construct. For example, the kinetic qualities of physical models are very important. In this experiment the hypar paper model is kinetic and is built with respect to the characteristics of the digital construct. The kinetic physical model interacts with the parametric-associative model and vice versa though the mediation of the designer and the computer screen.

This encourages the designer to create a bond between different, incongruent mediums or models. Through the confrontation of two incongruent mediums, the cross link allows the designer to invent completely new features and elements that the initial system does not possess. It enables progression and the emergence of new features in the exploration by hybridising disparate mediums. For instance, in Experiment 5 a cross link between the hypar surface and the paper was created that gave birth to the fold as a design feature. The fold was not an inherent part of the initial mediums: it was invented and introduced by the designers as a feature that would bond the paper with the hypar geometric concept and allow the design
process to progress. In contrast to the feedback loop, which leads to the reformation of a model by synthesising the results of subsequent models in a chain, the cross link is created between two parallel models to create a bond in an open-ended fashion. Compared to the bidirectional link, which emphasises the change in the direction of design influences between two linked models (that is, between driver and driven), in the cross link the two mediums do not drive one another but are merged by means of a new feature or mechanism that bonds them.

Goal-oriented versus open-ended approach
Two approaches can be taken to computation in the exploration: goal-oriented and open-ended. While the former refers to the use of computation to realise the designer’s idea and intention, the latter refers to the use of computation to aid the designer in ideation. In a goal-oriented exploration, before any exploration begins, the designer has conceptualised the design, assumed the end product, and predicted the challenges. The models, mediums, and tools are utilised to embody the designer’s predicted design challenges and are linked together to fulfil the designer’s intention. In other words, models, mediums, and processes make it possible for the designer to reach a specified goal. In the open-ended approach, the challenges are poorly defined or have not been assumed at the beginning of the exploration. Ideation—the conceptualisation of design—occurs throughout the process. Through the application of known constraints in an open-ended fashion, new and unexpected problems occur in the course of the exploration for which new solutions are sought. As the designer’s cooperative work with processes proceeds, the exploration model is shaped, new knowledge is achieved, and design is conceptualised. Here, the design process has a significant impact on ideation and the designer’s intention.

Three kinds of exploration model
From the experiments, the thesis identifies three kinds of exploration model. These exploration models differ in the way they emerge as the designer creates interdependencies. This includes the difference in the kinds of links, the designer’s approach in creating interdependencies in relation to the ideation, and the kinds of models and mediums used in bringing constraints into exploration, all of which impact the emergence of the exploration model.

Circular and uniform exploration model
This model, which is commonly used in the field of digital design and digital fabrication, is explored in Experiment 1, Honeycomb, and Experiment 2, Strip. It uses computation for integration with an emphasis on conformity between the different aspects of the building project. Circular links are created between the models in a design-to-production chain to produce a feedback loop. Models of different kinds are matched to conform to one another in the cycle of design to production. In this model, the influential aspects of a design project are assumed prior to beginning the exploration. In other words, the goal-oriented exploration already contains an assumption about what is to be designed. Models that incorporate constraints into the exploration are circularly linked to each other based on the designer’s
assumption about their interdependencies. Connecting subsequent models to earlier ones informatively in a circular fashion, the designer’s formal intention is investigated and reformed. Solutions to the problems of fabrication can be incorporated in advance, and new problems encountered in the course of the design-to-materialisation process can inform the formation: little by little, form takes on its character in every cycle of design to production. A risk in using computation alone in an exploration is shown in this model: the exploration is made uniform, and diversity, creative operation, and unforeseen findings are reduced.

**Branched, incremental, and diversified exploration model**

This model is developed from Experiment 3, Hypar. The exploration model is a digital-physical hybrid, and emerges from the incremental incorporation of constraints into the exploration domain. The exploration is treated as a drifting design problem in which the influential aspects are poorly defined in the beginning and new influences are incrementally introduced at every step. The exploration grows and is open-ended. New features can emerge from cross-linking incongruent physical and digital mediums that possess the constraints. This model points towards the significance of using computation not merely as a means for realising the designer’s intention, but rather as a means for ideation. It promotes the diversification of the mediums that incorporate constraints in order to increase the potential for creative exploration and significant findings. However, it also shows that diversification alone is not enough to allow creative exploration. The designer’s approach and the way these diverse mediums are synergised are significant factors. For example, Experiment 2 also practiced the establishment of constraints in the exploration through diverse mediums—paper and the developable surface—but the goal-oriented approach limited the exploration.

**Parallel and bidirectional exploration model**

This model emerges from Experiment 4, Paraboloid of One-Sheet. It involves the simultaneous linking of multiple mediums and models of different kinds to a node model bidirectionally and exploring of design alternatives at the same time. While in the circular and incremental exploration only one event occurs at a time and there is a hierarchy of driver and driven, in this exploration model the direction of influence can change. The role of driver and driven can be switched, and multiple events can occur simultaneously. The bidirectional links between two models or mediums allow the designer to explore the design in two directions. A design solution is found when the two frontiers of exploration meet.

This exploration model encourages a less restricted use of computation and encourages the designer to take agency in the exploration and to bend the rules. Because computation, like any other means of design, has its limitations, the designer should take the initiative to tweak the process rather than let the exploration be governed by the limitations of tools. For example, when the feedback loop is the only mechanism for nonlinear exploration offered by computational tools, and there is a need for reversed dependencies, the designer can overcome this limitation. As exemplified in
Experiment 4, simply by creating physical models and mediating between digital and physical models the designer can create a human-assisted bidirectional link and invent other ways of exploring design. This suggests that design exploration is not the application of a predetermined computation process, but rather a more complex process that relies on the designer’s way of conceptualising and formalising design.

7.1.5. Ideation, the design exploration model, and the designer’s approach

The exploration model can be viewed as a means to realise the designer’s idea or as a means for ideation—that is, for generating ideas. In other words, it can help to refine or find ideas.

It is common that in the first stages of a design, ideas occur in the designers’ minds and also come out of brainstorming among team members discussing the concept. The idea can be embodied in an exploration in different ways. This can be accomplished using a single model or multiple models, and in the way multiple models are linked together. This is examined in Experiments 1 and 2, in which the designers’ idea of generating a geometrically complex form with respect with climate, structure, and fabrication is embodied in sets of models and the ways they are linked—for example, linking the CAD and CAE models generatively to alter surface form in relation to the wind direction of the site in Experiment 1. Four disparate kinds of models were created—geometric, CAE expert, computer-generated physical, and manual physical models—and these models were linked to one another in a generative way.

Another approach is to find the design idea through the tools, models, and materials. Proceeding to Experiments 4 and 5, the emphasis is on the mediums of design instead of on models. Material, geometry, and algorithm are not only the representational mediums of the single models but are means through which the designer thinks, sees, and makes. The designer can choose any of the mediums to establish the constraints in the exploration, without having any concept in mind. Then, by interlinking the mediums in an open-ended manner, the designer can, through the exploration, find and form new ideas.
7.2. Significance in the field

The theoretical case for integral computational design and digital fabrication needs to be revised in order to further embrace both the designer and manual physical model making. Manual model making is only meaningful if it performs a specific task in the process in relation to the research question. For instance, the manual manipulation of paper strips in Experiment 2 is meaningful in the context of the design question that is being explored. Another example is Experiment 4, in which physical models are developed to change the direction of design and overcome the limitations imposed on the exploration by computation.

The exploration models developed in this thesis suggest that the achievement of significant findings, invention, creativity, and progression is accomplished through cooperative work between the designer, physical modelling material, algorithm, and geometry. In his dissertation, Kilian frames the need for heterogeneous, integrative modes of design exploration, leaving open the question of what such an integrative exploration model might be like (Kilian 2006, 314). This thesis examines how physical and digital models can be combined in a progressive and generative manner. For the algorithmic exploration model to produce significant invention, the designer must play a significant role. The designer does so by choosing one medium over another when formulating the design problem and establishing design drivers from the set of constraints, by linking the design mediums to one another and determining the kinds of interdependencies between them, by translating between design representations, and by describing the key aspects of the exploration in terms of algorithm. At the same time, the way the designer works with the models and their mediums in the exploration model is constrained by the mediums themselves, their possible linkages, and the set-up of the exploration, which emerges gradually.

7.3. Limitations of the experiments

Conducting the experiments for this research was limited by time and economic factors as well as by the availability of fabrication tools. However, such limitations are similar to the realities of actual practice, where cost and available fabrication methods continually constrain the design and lead to pragmatic decision making. Similarly, sometimes an experiment had to be concluded due to the time constraints of the course in which it was carried out, which led to certain decisions and to the rejection of some design options.
7.4. Future direction for the research

An actual architecture project is multi-constrained and involves the use of diverse materials and their fabrication techniques. It therefore needs meaningful abstraction on different levels. A building will not be built with a single material, a single technique, or a single structural system. Computational models and systems must be developed that allow for cooperation between diverse materials, fabrication techniques, and structural systems already in the early design stage. For example, when combining additive with subtractive manufacturing techniques in a design project, computational techniques must be developed that bridge the mesh geometries and the NURBS geometries that are fundamental to their respective fabrication techniques. Yet the new computational model must extend far beyond mere technical solutions.

Computational methods can help architects to link disparate entities in a design exploration—for example robotic operations, sketches, simulation models, small-scale models, and 1:1-scale prototypes. Considering the significant role of the designer and design as an active choice, the design exploration cannot be narrowed to a single computational technique and single mode of design: “One should not make oneself the slave of one tool only. That is why I always work with proper drawings from the drawing board, with sketches and with models at the same time” (Gänshirt 2007, 21).

The question that this research raises for future research is, how do we develop computational tools for design exploration in such a way that they allow cooperation between the designer’s different modes of design—thinking, seeing, and making—and disparate design mediums in an open platform for design. Can computational tools and methods overcome the limitations of conventional tools by allowing cooperation between different modes of design and therefore the designer’s different activities?

In addition to customizing design tools, the author suggests exploring architectural expression in the meeting of different tools, mediums, models, and ways of design. When hybridising digital fabrication techniques (e.g., subtractive and additive methods), materials (e.g., wood and fibre-reinforced plastic), kinds of geometry (e.g., mesh and NURBS), and methods (e.g., analytical and generative), what are the new languages and expressions for architecture? The cooperation between these diverse elements can inform architectural development. As a designer, the author is curious to know the architectural potential of combining two or more different ways of design. From such possibilities new and unseen architectural languages can be developed.

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7.5. Algorithm as the backbone of the exploration model

Without a doubt, it is necessary that architecture overcome its current focus on the isolative use of computation and digital fabrication, which is a strictly logical and descriptive mode of operation. This dissertation calls for a rethinking of the way architects are using digital tools in order to enhance the designer's experience, diversify the exploration, and aid in ideation. It examines the parallel and integrative use of multiple design mediums to influence and constrain the exploration, and draws attention to the need for diverse models, mediums, and tools. It points towards the interdependencies that already exist between geometry, algorithm, material, and tools, and the interdependencies that can be created by the designer throughout an exploration. The dissertation also draws attention to the designer's activities in the exploration, the prescriptive characters of mediums, and the tension that exists between them.

This dissertation sheds light on algorithm's potential for engaging the designer and allowing for the diversification of the designer's mode of operation and of the exploration. In doing so it elevates the application of algorithm in the design exploration beyond merely incorporating fabrication constraints, viewing it more as the backbone of the exploration model. As the backbone of the exploration model, algorithm can allow the designer to link disparate entities in a design exploration to one another simultaneously. By defining new interdependencies, architects can gain new insight, achieve unforeseen results, and reform the initial intentions. Algorithm can be a means to expand and diversify the design exploration, rather than confine it to digital conformity. It can aid in design ideation, which is at the core of the design practice.

Today, with the extensive use of robotic arms and computational tools in architecture, we are in the middle of reshaping our understanding of the roles of design, the mediums of design, and the designer, as well as the kinds of relations among them. This dissertation is pushing towards breaking out of seeing design as merely the carrying out of a predictable workflow, and design mediums as merely enclosed categories within digital or physical models. It does not provide a definitive answer to the question of what is the best way of using computation in the exploration, but by pushing the boundaries of how it can be used in relation to diverse mediums of design it demonstrates the significant role of the designer and the need for diverse models, mediums, and tools in the exploration as well as diverse modes of design exploration. The real challenge lies in developing computational tools in such a way that they allow cooperation between different modes of design and disparate design mediums in an open system.
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This doctoral thesis book is a result of the author's practice-based research in the field of digital design and digital fabrication in architecture. The significance of her work lies in designing and building full-scale prototypes in order to explore the possibilities and limitations of computer-based design and digital fabrication. In this dissertation book, she demonstrates and reflects on a series of practical projects carried out with students in the architecture and engineering schools and places them in a theoretical context.

The book explores the strong links that the author sees between the descriptive domain of generative computational processes and the empirical domain of materialisation. Throughout the book, the author speaks about exploration domains—design spaces that can be created using disparate mediating artefacts, in particular models, algorithms, computational geometries, and materials. The role of the author’s practice and her focus in this dissertation book is to clarify the actual interdependencies that exist and can be created between these mediating artefacts. Finally, by revealing the tension that exists between computation and material practice, she emphasises the significant role of the designer in computer based design.