Adaptive Parameterisation:

Methods for employing flexible data structures for complex modelling practices in architectural design

PhD Thesis by David Stasiuk

Colophon

Thesis Title	Adaptive Parameterisation: Methods for employing flexible data structures for complex modelling practices in architectural design
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Abstract

This thesis is concerned with the feature space that defines the inputs and outputs of parametric models for architectural design and project development.

As computational design methodologies continue to mature in theoretical and applied terms for both academic and professional practices within the building sciences, the modelling processes, systems and setups they employ become increasingly specialised and powerful. A proliferation of authoring tools and programming libraries enables the deployment of computational algorithms that support: increasingly sophisticated generative modelling techniques; improved simulation capabilities; models that are informed by material properties, and indeed may program matter themselves; design systems modelled across multiple scales; improved analytical and evaluative techniques; and continuously advancing digital fabrication processes. Within a given project, a collection of such discrete and variably-purposed systems or representations operates as a network of partial models. As the number and variety of functions for these partial models increase in complexity then, so the information thresholds – or parameter spaces – between them similarly become more numerous, and crucially become increasingly essential to efficient and robust project design, development, and delivery.

This thesis presents Adaptive Parameterisation as a modelling methodology – within both theoretical and applied frameworks – that focuses on the formulation of this feature space for its potential to improve the performance of model networks in the building sciences. This approach relies on the development and deployment of parameter spaces whose data structures work as mutable substrates for managing and conveying the increased design intelligence created through the dynamic activation of algorithmically-driven, computational modelling systems. This thesis describes how certain data structures may better support the establishment and implementation of bi-directional constraints between partial models, eliciting increasingly holistic performances from the various, discrete partial models that are necessarily bound together in the realisation of architectural projects. It examines data structures that improve both the descriptive depth and breadth for the parametric models they inform, and which further clarify the purpose of each partial model, while assisting in negotiating the emergent heterogeneity of these purposes across the model network.

Preface

This thesis reflects the written component of a PhD project undertaken at the Royal Danish Academy of Fine Arts, School of Architecture. The research was pursued at the school's Centre for Information Technology and Architecture (CITA) as a component within the larger Complex Modelling in Architectural Design project, funded by the Danish Council for Independent Research (DFF) through the Sapere Aude Advanced Grant, which was awarded to Prof. Mette Ramsgaard Thomsen. Prof. Thomsen is also the head of CITA, and supervisor to this PhD project. The objectives for the Complex Modelling project include critical engagement with inter-scalar feedback loops and the investigation of computational systems that enable their dynamic modelling using such techniques as machine learning and material simulation, while retaining a focus on how the intuitive, creative and communicable dimensions of architectural design may be retained in their application. It questions the established data infrastructures that define and constrain contemporary CAD systems and aims to present alternative methodologies that support the evolution and advancement of increased representational potentials for digital modelling systems. This PhD project strongly privileges its collaborative role within the Complex Modelling framework.

This thesis is being submitted to obtain a PhD through publication. It is comprised of three main parts. Part I consists of an introductory chapter, a methodology, and a theoretical framework. These aim to establish the main themes that animate the research project, including its motivation, contribution to knowledge, mode of inquiry, epistemological concerns, and contextualisation in contemporary discourse. Part II consists of a selection of seven peer-reviewed publications to which I contributed during the research project's duration, which include six conference papers and a book chapter. These papers reflect the ongoing discourse produced chiefly through the design experiments that constitute the main body of my research through the PhD project. Part III is comprised of a brief concluding discussion of the primary contributions for the project and their relationship to practice.

Notes on the text

Except where noted in the figure captions, all other images shown in this publication were produced by the author. References to other text are supplied at the end of each respective chapter in which they appear.

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Beyond their friendship, they have shown me how critically reflective practices can span academia and the professional domains. Between studying under them at Rensselaer Polytechnic University and working with them at Method Design, their impact on my own practice has been immeasurable. I am also very deeply and similarly grateful to Niels Jakubiak Andersen, Kenneth Skytte, Hasse Selvig Sandell, and Klaus Stub Dyhr of Krydsrum Arkitekter. I am humbled by their generosity in hosting me at their office during my first years in Copenhagen, and am especially thankful for their sharing knowledge, providing mentorship, and affording me the opportunity to contribute to their practice. I would also like to thank my colleagues at Proving Ground – Nathan Miller, Kristen Schulte, Steve Sanda, and Trygve Wastvedt – whose patience, humor and support have been essential as I've completed my dissertation, and with whom I have been lucky enough to try to apply in practice some of the findings described in this document.

Of course without the continued love and support of my family in all regards, I could never have accomplished any of this. Thank you, Philippa, Iris and Jane, for everything.

Contents

Part I: Framework

1. Introduction

The PhD project presented in this dissertation investigates the practice of complex modelling using computer-aided design (CAD) systems for architectural design, project development, and delivery within the building sciences. It is principally concerned with the relationship between architectural design practices and the continuously emerging digital technologies they employ.

This chapter introduces the research project in three sections. The first section presents the project framework. This introduces the key concepts and aims toward contribution to knowledge. Additionally, it explores the research questions that have motivated it, as well as the principal vehicles for inquiry that it has relied on to pursue these interests. The second section presents the background of the project, contextualising its interest relative to some of the interests and concerns that affect contemporary architectural practice. It more broadly discusses computational thinking and the impact that the evolutionary nature of digital technologies has on computer-aided modelling. The third section presents concluding remarks and outlines the structure for the remainder of the dissertation.

1.1 Project framework

This research project engages in the formulation, development, and deployment of digitally situated, complex design models for architectural design. It is chiefly interested in computational modelling, which may be defined primarily according to its use of algorithms to compute or produce new information about target design systems, to transform, modify, re-arrange, or order observed physical or symbolic entities. It engages these modelling methodologies both in their direct application through project work and investigation, and through reflection as topics of theoretical inquiry. This section presents an overview of the research questions, hypotheses, main arguments, and claims toward contribution that comprise the body of this thesis.

1.1.1 Toward holistic model networks

The central interest for this project is the formulation of integrative computational modelling methodologies for the development of systems that exhibit holistic behaviours in how they support processes of invention, project development and analysis, and delivery. To successfully achieve this, they must be able to support the investigation of a broad range of design concerns while achieving in parallel the requisite depth in representational detail for project development and resolution. The span of operations that address these requirements are then necessarily comprised of multiple, discrete, but interdependent elements. Each of these elements is in turn responsible for integrating key design or production goals from different stages or aspects of the project into a global configuration. At one end of this spectrum of concern, these elements are responsible for nurturing processes of invention and discovery that facilitate design sketching, prototyping, and the development of designer intuitions regarding the behaviours of often exploratory or experimental material assemblies. At the other end, they must produce representations of the design system that not only successfully convey fundamental intentions related to concept and form, but also for effective performance evaluation; ultimately, they must possess the flexibility and robustness to command, control, or otherwise direct sophisticated methods of fabrication, assembly, and installation. Within this domain, successful models are comprised of interstitial but well-integrated generative engines and analytical systems that support these multiple modes of design development. This emergent ecology of diverse instrumentation and varied representation will be referred throughout this document as *networks of partial models.*

When constituent models within networks of partial models are formulated and developed following strategically conjunctive methods such that they are integrated as part of a holistically behaving whole, they form a collection that can be productively understood as an effective model network. Model networks developed in this fashion are defined partly by the richness and depth of the representations they generate, command and control, and partly by the quality and nature of the interfaces that exist between each discrete, functionally specific component, or sub-model. Model networks as defined here aim to manage this organisation of their composite elements such that each is both nimble in its capacity to perform specific tasks, and robust in its ability to transfer critical information across the model network.

1.1.2 Adaptive Parameterisation

This research project presents a*daptive parameterisation* as a method for formulating and developing complex computational design modelling systems. This dissertation is predicated first on the assertion that nearly all contemporary architectural design projects of even modest complexity are realised through collections of interdependent partial models, each of which is possessed of different information-producing or representational functions. Adaptive parameterisation aims to elicit increasingly holistic performances from these networks of partial models by focusing on the data structures for the parameter spaces that operate as the information thresholds between them. In adaptive parameterisation, these data structures should work as *mutable substrates* for managing and conveying the increased design intelligence that is produced through the *dynamic activation* of the algorithmically-driven, computational modelling operations embedded within each partial model. At object scales, mutable substrates are defined as *topologically open-ended* but *organisationally-persistent* data structures. They should function as synthetic information carriers whose geometric elements may be directly imbued with locally differentiated but semantically rich, descriptive information. These data structures are noteworthy for their mutability: through recursion and feedback loops executed within the algorithms they interconnect, they must be able to flexibly adjust in number and relationship to one another. At model scale, while they are locally adaptive to the needs of a given model's function, their persistent qualities are designed to maintain alignment and bridge between disparate elements in discrete partial models, supporting the increased descriptive potential of each model's algorithmic function by passing information within and between models. Crucially, these mutable substrates are dynamically activated through each discrete partial model's algorithmic methods. Individually, these may accumulate, transform, integrate, and command underlying elements across the range of the project's demands for design and realisation. Through adaptive parameterisation and the mutable nature of the underlying data structures that parameterise each partial model, feedback loops and multi-directional constraints are enabled that allow for the increase of information-producing potential between them. Dynamic activation applies to specific model functionality in element transformation. For example, it includes (among other purposes) the implementation – either independently or conjunctively – of simulations, structural analysis, or complex detail resolution. But importantly it also aims to address and explore parameter space itself: if the parameters that define information thresholds within and across models become capable of achieving emergent behaviours in how they engage and enhance the algorithms they inform, then our design systems may become more creatively intelligent, endowed with epistemic autonomy and eliciting holistic performances from design models that allow for increasingly complex collections of model elements and algorithmic transformations to exceed the sum of their parts.

1.1.3 Research Questions

The development and presentation of adaptive parameterisation as a method for complex model formulation has emerged through a series of research questions that are motivated partly from my own prior experiences in professional practice but have been further transfigured through a critical engagement with experimental research and contemporary discourse over the course of this research project. In this sub-section, I present these questions and their attendant hypotheses. In subsequent sections, these questions will be framed by the discursive background that has informed them.

What modelling and practice-based frameworks are well-suited to negotiate the continuously evolving and complexifying technological and theoretical ecosystems manifest in contemporary architectural design?

If technological advancement continues its current course of development, it becomes increasingly important to identify and articulate modelling frameworks that support an effective design practice that may not only effectively negotiate the increasing variety of available tools, but best maximise their potential in application. Within the larger framework of CAD, this research project aims to demonstrate that computational modelling approaches embody a unique set of potentials for engaging the continuously widening range of model typologies and functional intentions that are emerging in contemporary design practice.

What computational modelling methods may be used to elicit increasingly holistic performances from the disparate partial models that comprise model networks?

Parameter spaces – or *feature spaces* – are foundational to computational design models. A parameter space is comprised of a collection of descriptive features which organise initial model conditions and supply the algorithmic elements of a given model with on-going references for decision thresholds and dimensionality, keying the execution of the model's procedurally-driven decision processes. Furthermore, performance criteria for the evaluation of iterative design processes are established and managed in a model's parameter space. Variations of parameter values as both input and output – through some mix of systematic, logical, and intuitive actions – empower the designer to interrogate the parametric model and test or leverage whatever capacities it may have for: design exploration; analysis and optimisation; versioning; localised deployment; and fabrication interest. Through a deft application of the parameterisation process, a designer can implement second-order, procedural modelling methods, wherein relationships between an initial set of conditions and an algorithmic process become the means for generating new architectural information.

With an understanding that they define the explicit thresholds that exist between partial models within larger networks, this research project identifies parameter spaces as a topic of special inquiry and asks how they might be formulated in such a way to produce a greater synthesis between partial models, toward increasingly holistic performances of model networks.

How can the parameter spaces that exist as thresholds between partial models begin to exhibit epistemic autonomy?

A further motivation for this research project has been to explore methods for formulating better integrated open-ended design systems. In discussing cybernetics, Peter Cariani argues that "open-endedness is an important goal for designing creative systems. Creative systems are needed when we face ill-defined problems that defy direct solution, when we don't know what observables...and actions...are needed, and how they should be coupled and controlled." (Cariani, 2008) It therefore is concerned with modelling systems that rely on generative logics and open-ended modelling systems for design production.

Computational modelling systems perform explicit transformations of base parameters for the generation of new intelligence about a target design system. An aim for this project is to demonstrate that networks of partial models effectively formulated can manage multiple sequences of such transformations in the production of tightly integrated architectural material assemblies, while simultaneously leveraging them as open-ended operators engaged in goal-seeking behaviour. Cariani argues that cybernetic models can be developed in such a way that they are capable of evolving new feature sets, effectively becoming endowed with a form of epistemic autonomy. The three primary behavioural constructs he identifies for cybernetic models (sensing, thinking, and acting) have corollaries in computational design models (parameterisation, algorithmic processing, and implementation). This research project explores the potential for dynamic and evolvable parameter spaces for their potential in activating epistemic autonomy in computational design models.

1.1.4 Argument and contribution

Especially for practices that privilege computational modelling approaches, it is recognised that the makeup of underlying partial models within larger networks are varied according to both type and intent. For example, while certain models may be responsible for leveraging "bottom-up" algorithmically-driven agents to enact complex algorithmic transformations, others may necessarily be deployed through more rigid, "top-down" interventions from the designer. So, as modelling tools increase in their number, specialisation, and usage, they are inevitably characterised by similarly varied theoretical natures, potentials, and functions. This research project suggests that more singular frameworks for conceiving of and understanding the theoretical concerns for digital modelling are therefore not only narrowing, but furthermore problematic and ultimately intractable. The position taken here instead advocates for an approach to digital modelling that is fundamentally inclusive and by design accommodating to this increasingly *heterogenous* ecology of both instrumentation and theoretical positioning. This contrasts with practices that advocate for theoretical, ideological or instrumental *homogenisation*.

I also argue that effective model setups for engendering holistic performances from such networks can critically engage this heterogeneity through the establishment and deployment of flexible data structures that ensure that the information produced along each stage of the supply chain effectively interface with others, such that wide ranges of design concerns may not only be reconciled, but also used to enhance the performance of each other. The aim here is not to articulate a singular approach to developing solution spaces through design modelling, but rather to present a generalised methodological framework and theory of practice that supports the negotiation of the continuously increasing diversity of modelling environments presented in contemporary practice, in terms of both large-scale technological platforms and project-oriented workflows and configurations. I furthermore aim to outline both theoretical and instrumental mechanisms that allow for the amplification of designer capability, nurturing processes of invention and discovery, and taking advantage of the incremental intelligence afforded through algorithmic transformation and simulation. These arguments are intended to be fundamentally *conjunctive* in nature, building upon and integrating within existing frameworks, and especially endeavouring to bridge approaches that may either appear at odds or have indeed been in some cases theoretically situated to appear mutually exclusive to one another. In pursuit of this methodological framework and theory of practice, this research project presents *adaptive parameterisation* as a modelling approach for eliciting increasingly holistic performances from complex model networks.

This research project's claims to contribution are threefold. First and foremost, it presents *adaptive reparameterisation* as an applied modelling method that focuses on the information thresholds that bind partial models to one another, with an aim to activate bi- or multi-directional constraints between discrete model elements within open-ended design systems. As a secondary contribution, it presents the *digital-material practice* as a theory of practice that anticipates and enables adaptation to the continuous changes to the technological and theoretical landscapes that surround CAD and computational modelling interests in contemporary architectural practice. This theory of practice is an extension of several action-oriented research methods, and is directly reflective of the research approach employed throughout this project. It focuses on a direct and catalytic relationship between design experimentation and discursive reflection for knowledge production and theory-making. Finally, this research project has produced a collection of multiple digital design tools and algorithmic implementations that have been publicaly and freely disseminated to the computational design community. While some of these digital instruments have been developed and deployed specifically within the context of the design experiments that comprise the centreal body of this research projeet, there are presented here both for their direct value to the design community, and importantly as furhter demonstrators of the relevance of the digital-material practice.

1.1.5 Principal vehicles of inquiry

The proliferation of new design modelling technologies for contemporary architectural practice has created a sense of urgency to the enterprise of developing data infrastructures that are at once both more flexible in their ability to support information exchange across modelling platforms and robust in their ability to produce, manage, and ultimately leverage more powerful information-producing algorithms and the greater volumes of design information they create. The increase in both the number and specialisation of emerging design technologies creates an opportunity for eliciting improved performances, but is also attended by an increased risk of fracturing along the supply chain, leading to error and inefficiency in project design and development. This continuous transformation of design modelling technology then defines a broad problem domain from which this research project takes a key point of departure, which is in its focus on the parameter spaces that bind disparate systems with one another within a network of partial models. This research project has been undertaken through the exploratory discretisation of this overall problem into a series of vehicles of inquiry. These vehicles of inquiry that have been thus employed embody problem domains that are both targets of epistemological interest and may be activated directly within design modelling practices, chiefly through existing methodological frameworks.

The vehicles of inquiry for this research project have emerged and been applied in both parallel and sequentially through the catalytic process of investigation and reflection embedded within digital-material practices, which are explained in greater detail in the following chapter. Here it should be understood that these vehicles of inquiry are topics that form a critical basis for engaging in action-based dialogue with contemporary discourse, through the use, enhancement, and development of related and evolving digital modelling tools and methodologies. These are *Open Topologies*, *Design Simulation*, *Agency as a Continuum*, *Machine Learning*, and *Multi-scalar Modelling*, each of which are introduced in this section.

Open Topologies

Peter Cariani describes cybernetic design models as being comprised of three primary behavioural constructs that interact with each other dynamically in their execution as an operational system. These are *sensing, thinking* and *acting*. Sensing describes the process of a model gaining information about the external world, thinking represents the coordination process of choosing appropriate actions given the world as it is sensed, and acting is the process of influencing courses of events in the world. This conceptualisation of a modelling space as a continuously operating instrument strongly resonates with the challenges that face the architectural modeller who is relying on procedural systems to enact design solutions. Cariani also asserts that "open-endedness" is an important goal for designing creative systems:

> *"Creative systems are needed when we face ill-defined problems that defy direct solution, when we don't know what observables (sensors, features) and actions (effectors) are needed, and how they should be coupled and controlled (coordinations, computations). In these cases, we want the system itself to come up with a solution that we have not in some sense foreseen." (Cariani 2008)*

Most historical modelling methods, especially as they relate to operation across the supply chain in realising building projects, have relied on the *topological fixity* of underlying design and data elements. Here, topology does not refer to the mathematical description of shape – such as an object being either a disc or a torus – but rather to the *number of* and *connectivity between* a set of values or objects. For Cariani, these objects or values can range from the abstract (such a set of descriptive properties) to the more real (such as components within a physical building assembly). In the context of architectural design, while constraining the topology of constituent elements may simplify the operation of more straightforward supply chains, it does so through the simultaneous introduction of rigidity or inflexibility into the model space. For more straightforward modelling problems where the parameter space between models can be expected to remain unchanged, this may behave as an asset. However, this type of fixed topology requires that partial models within a network operate either independently or in sequential dependence. When models are thus formulated in conjunction – in addition to limiting that capability for adaptive or open-ended design pursuits through the exploration and integration of unknown observables, actions and controls – this furthermore *increases their fragility* in the event of missing initial data: when changes in a partial model are consequential to separate models which are blind to these changes, there is a risk for error or failure.

This research project pursues the hypothesis that the application of systems that instead employ open topologies enables an alternative approach where individual partial models may not only adapt to changes within their input parameter spaces, but also be empowered to create multi-directional dependencies within the model network, exhibiting higher resiliency to changes in the design environment and producing richer feedback loops for increased design intelligence. Whereas there is a necessary increase in complexity in the formulation of open topologies such that a given individual partial model must be equipped to respond or adapt to changes in its parameter space, I argue that the resulting model network will ultimately be more flexible, robust, and capable of increasingly preferred holistic performances.

Design Simulation

Simulating systems of interest has been a principle goal of digital computer systems since their introduction in the middle part of the 20th century, with an aim to more effectively analyse, predict and investigate the behaviours of these target systems. As simulation techniques have become increasingly sophisticated and computing power has followed its exponential trajectories of growth, digital simulation has become both ubiquitous in and indispensable to the natural sciences and engineering practices, and in many fields of study has matured to the point where digital simulations of target systems have become proxies for physical experimentation.

Although the building sciences have long relied on digital simulation systems as instruments for evaluating the performance of a designed condition – some examples include using finite element methods to determine the viability of a structural system under specified loading conditions or using ray-tracing techniques to determine light quality or insolation – it is only more recently that architects have begun to employ digital simulation systems for form-finding or generative design operations. While there are many potential applications for simulation along these lines, this research project has chiefly focused on the potentials for engaging in design modelling operations that are informed by plausible representations of material behaviours and structural performances during morphogenesis. It pursues the hypothesis that through these types of simulation, the designer may engage in form-finding techniques that nurture processes of invention and discovery that directly embed and activate the underlying material characteristics of constituent assembly systems to produce novel, inductively integrated solutions to complex design problems. This research project explores how simulation algorithms may be used in conjunction with carefully crafted underlying data structures that allow not only for this increased intelligence to be read in the context of the modelling environment in which it is implemented, but to be coupled with processes in other partial models, aimed toward the application of bi-directional constraints. Importantly, the demonstrations of simulation are presented as a general framework for use within any simulation systems that allows for computational models to generate increased intelligence about target design systems. The application of design simulation as a dynamic activator for data structures that behave as mutable substrates is a central means to develop and test processes of adaptive parameterisation in complex model networks.

Agency as a Continuum

The terms *top-down* and *bottom-up* as modelling approaches for producing design solutions are most often understood in relation to one another as poles in a methodological dichotomy. In this view, a top-down design method describes an explicitly-directed, fully-bound and centralized approach. This orientation suggests that the designer's intention is full in scope and attended by an assumption of prior knowledge in relation to both problem and solution spaces, and effectively considers that the designer is the exclusive agent in a design process. A bottom-up design method then refers to an implicitly-directed, unbound and decentralized approach, operationalised through local interaction and with a shorter and more immediately responsive scope of vision to be applied for the negotiation of the decision space. In this view, bottom-up design models then exhibit tendencies for step-wise dynamic morphogenesis, with the configuration of components functioning through agencies afforded by local intelligences and stochastic interdependencies between elements.

This research project considers the fixed designation of these methods problematic. In *A tentative classification of goal-seeking behaviours*, M.P. Schützenberger addresses the similarly fixed binary classifications of the *strategic* and *tactical*. He presents a view of the strategic – that maps to a top-down approach – whose application similarly using prior knowledge of a total target system for an exhaustive and frequently complicated search of its solution space. This then contrasts this with a view of the tactical – that maps to a bottom-up approach – which relies on localised knowledge for a smaller scale decision space, which is deployed sequentially in smaller temporal steps. Schützenberger creates this setup to define both the strategic and the tactical as methodologically identical, but only differentiated by the different scopes of vision, available knowledge, and scale of the goal-seeking decision being made. By collapsing them into a continuum that varies not in fundamental form but rather in "span of foresight", he creates a nuanced understanding of goal-seeking systems.

This research pursues the hypothesis that this consolidation similarly applies to top-down and bottom-up approaches to design model agency. The suggestion is that partial models which are formulated with active concern for their location along this continuum – where the designer and the design system may both contribute varying parts according to the purpose of each partial model – are improved through their precisely defined purpose, especially regarding the calibration of their shared parameter spaces.

Machine Learning

Machine Learning is a field of computer science that has had an increasingly transformative effect across a broad range of industries, providing insight, analysis and decision support for a wide range of tasks. The computer scientist Tom Mitchell defines machine learning through the assertion that "a computer program is said to learn from experience *E* with respect some class of tasks *T* and performance measure *P*, if its performance at tasks in *T*, as measured by *P*, improves with experience *E*." (Mitchell 1997). Within this framework, machine learning algorithms can be considered according to three areas of interest: task-oriented processes, cognitive simulation, and theoretical analysis. Most contemporary applications of ML are concerned with task-oriented machine learning algorithms – and this applies to architectural design – which are principally focused on the classification or prediction of data points within feature domains of discrete or continuous data types.

Machine learning is closely related to – and sometimes considered interchangeable with – the field of statistics. For this reason, fields of study or professional practices that are rich with large volumes of well-structured data and pressed by clearly articulated problem domains have been better suited to position machine learning techniques as central to their methodologies. So, while both professional and research-based architectural practices have seen some adoption of machine learning for design, decision support, and improved fabrication processes, because of their relative dearth of well-structured data sets and the open-ended nature of the design problems, they face significant challenges for wide-spread implementation. Yet, for this research project, machine learning presents an interesting vehicle of inquiry for exploring adaptive parameter spaces: many machine learning algorithms specifically interrogate both the *content* and the *structure* of the parameter space in their application: Peter Flach refers to features as "the workhorses of machine learning," and highlights their transformational potentials, as feature sets formulated to support increased flexibility and dynamism present greater potentials for better predictive or functional capacity. (Flach 2012) This research project pursues the hypothesis that the use of machine algorithms may contribute to new modelling methods that privilege open model topologies and emergent feature production as critical operators in the generation of flexible and adaptive design solutions.

Multi-Scalar Modelling

Applications and techniques for the modelling and simulation of complex systems continue to both accumulate and improve in the natural sciences and engineering. These advances are being seen across scales, as, for example, material scientists begin to model micro-scale systems that describe the behaviours of matter at the molecular level, or marine hydrologists examine macro-scale systems that may describe ocean currents. As descriptive methodologies and their theoretical underpinnings become increasingly sophisticated, it becomes possible to integrate multiple approaches to describing the same system, simultaneously and at multiple scales. In such cases, micro-focused models may be used to describe areas of the system where a very high degree of descriptive resolution is required – and where a particular simulation method may be applicable – where macro-focused models may be used to describe areas of the system where a lower degree of descriptive resolution is acceptable for achieving adequate results and a different analytical technique is more approapriate. Such integrated modelling processes require special treatment for the different descriptive methods at the point of interface between scales: the "hand-shaking" mechanisms that enable each model to contribute to a holistic understanding of the system are central to its viability. (Winsberg 2010)

This research project considers multi-scalar modelling to be a rich vehicle of inquiry for exploring how model networks may be calibrated to exhibit increasingly interdependent, multi-directional feedback loops between partial models, enhancing design intelligence. Although this research project focuses on material systems as a principal target for engaging this pursuit, it hypothesises that because multi-scalar modelling approaches demand a rigorous focus on the parameter space that enables its constituent partial models to effectively inform each other, these types of modelling approaches should map across contemporary complex modelling concerns for architectural design.

1.2 Background

This section aims to frame this dissertation in its most general context by introducing key concerns that have helped formulate the research questions and interests that animate this thesis. These will be broken out into subsections, each respectively related to the field of interest, situation, and orientation of this research project.

The first subsection introduces the larger *Complex Modelling* project as a component within which my PhD research has been conducted. Since my experimental work has been pursued within this larger framework, it naturally has adopted many of the same interests, most significantly an investigation in the infrastructures of design models and their epistemology. It explicitly quesitons existing tools for negotiating information exchange within the design modelling supply chain, and pursues these through the vehicles of inquiry outlined in the previous section.

The second subsection identifies and introduces Computational Modelling as the general field of interest for this research project. Computational modelling is a subset – or extension – of CAD that employs the digital application of algorithmic processes for project design, development, and production in architecture and the building sciences. As a topic of inquiry, CAD encompasses a great diversity of both practical and theoretical concerns, and this section provides a summary of those historical components that are most relevant to the thesis. Although computational modelling exists as a component within this larger framework of CAD in general, the topic of "computational modelling" itself spans a wide range of theoretical interests. While the aim of this first subsection is partly to acknowledge the diversity of the concerns, opinions and approaches included in this range related to, it puts a greater focus on the shared characteristics that unify these varied positions and highlight their particular interest in computation for design modelling.

The third subsection regards the general acceleration of technological transformation broadly occurring in contemporary society, and not just limited to the building sciences. This thesis then situates itself in this context of rapid technological evolution and variegation, and focuses especially on the observation and relevance of this phenomenon for digital modelling practice in architecture and the building sciences.

The fourth subsection addresses a different but closely related type of continuously emerging variety: that of the broad diversity of theoretical interests that surround contemporary discourse related to computer-aided design. It examines how the idea of crisis has been central to this discourse. The notion that contemporary architectural modelling practice is in crisis is a shared concern for several different critical positions taken toward CAD. Yet many of these positions take starkly different positions relative to this concern, defining a multitude of arguments for both the precise nature of this crisis, as well as potential solutions for addressing it.

Together, these key areas of concern begin to frame an interest in how design practices might not only negotiate an accelerating complexity in the landscape of digital modelling instruments, but furthermore leverage it for the improvement of design quality and experience. They help to define the value potential for engaging in computational design as well as both the risks and opportunities afforded by an accelerating complexification of both model instrumentation and theoretical orientations. The last subsection synthesises these various concerns, and explains how they combine to provide a point of departure for the experimental engagement with modelling methodology that this research project has undertaken.

1.2.1 Complex Modelling

This PhD project has been pursued as a component within the larger *Complex Modelling in Architectural Design* project undertaken at CITA. Some objectives for the *Complex Modelling* project include a critical engagement with inter-scalar feedback loops and the investigation of computational systems that enable dynamic modelling processes, using such techniques as machine learning and material simulation, while retaining a focus on how the intuitive, creative and communicable dimensions of architectural design may be retained in their application. It questions the established data infrastructures that define and constrain contemporary CAD systems and aims to present alternative methodologies that support the evolution and advancement of increased representational potentials for digital modelling systems. The *Complex Modelling* project formulates and deploys new methods for extending "the digital design chain" to integrate "not only material systems, but also the composition of their components," engaging in the "specification of the materials themselves" with an aim toward the formulation of methods that reach from a research context toward architectural practice. (Thomsen 2016) These goals are also central to my research project, especially considering the stated ambition for my research project to prioritise the formulation of modelling methodologies that can accommodate multiple and varied design research concerns.

The *Complex Modelling* project has also been partly motivated by the observation that contemporary industry practice has at times taken a reactionary position to the relatively recent proliferation of powerful digital modelling tools. This proliferation will be described in the third subsection of this background as symptomatic of technological development itself, and, due to the availability of both visual programming languages and programming API's for existing design modelling platforms, exhibits autocatalytic tendencies toward an increase in both number and variety of tools that will be available to designers. The industry response to these changes has been to try "to standardise information and develop shared protocols between interdisciplinary partners," yet "core efforts such as BIM have proved inadequate in tackling the high degrees of complexity of current practice" or supporting "the needs for flexible, intuitive, and communicable design processes." (Thomsen 2016) My own professional experience prior to my engagement in this PhD project – and indeed in the time following the completion of my experimental work – aligns with these concerns. In a professional capacity as consultant, I have engaged in the specification of complex detail assemblies (Campbell, Comodromos, and Stasiuk 2012) and in modelling methods for managing complex geometry across multiple software platforms (Miller and Stasiuk 2017). In these examples (as well as within other projects) the tension between the structure provided by standardisation protocols and their frequently inherent inflexibility describes a concern worthy of critical engagement within architectural practice.

1.2.2 Computational Modelling

Since the development of the earliest CAD systems for architecture in the 1950's and 1960's, a broad subset of researchers in the building sciences has concerned itself not only with the development and application of digital instrumental instruments, but also with the epistemological implications for how architects might engage with computation, and in what ways that may affect quality for both output and experience of design practice. Architects such as Christopher Alexander, Nicholas Negroponte, Tom Maver, and others developed well-considered criteria for the role computers should play in making design decisions to truly be considered as "aids" in computer-aided design. Among others, these included applications for computation in applied mathematics for "relationship" modelling, using heuristics for search rules, and simulation for solution modelling (Maver 1970), using computation to identify and visualise relationships between design concerns to better understand the context and potential solution space for a design problem (Alexander 1977), and turning the design process into a dialogue between architect and computer that would alter the traditional human-machine dynamic (Negroponte 1973; Steenson 2015).

In so doing they began to formulate what would become enduring understandings of computational design theory. Despite this, and although they helped pioneer and test some of the earliest CAD hardware and software design systems, computers were at the time exponentially both more expensive and limited in power, memory, and flexibility; as a result, in important ways, epistemological and theoretical interests in CAD significantly outpaced their application in both research and professional practice. For example, in Architectural Intellignce, Molly Wright Steenson describes Negroponte's MIT-based Architectural Machine Group for having "experimented with systems that incorporated artificial intelligence, in projects that juxtaposed often grand ideas with limited and sometimes naive proofs-of-concept…[with them having] a goal for the convergence of spatial and informational interfaces." (Steenson 2015) As a result, although many of the ideas presented do endure in contemporary theoretical frameworks, consequential to these speculative exercises is that many early beliefs for how computers should have transformed the design process failed to materialise. For example, from very beginning of computer science, there was an expectation that machines manifesting some form of general intelligence would soon arrive, a belief that deeply informed many of the theoretical interests of early CAD researchers. By the end of the 1970's, this anticipation was repeatedly disappointed, and the theoretical frameworks argued for by CAD researchers were significantly altered. And just as certain expectations for technological advancement failed to occur, other unanticipated or problematic developments arrived. For example, as above, many early CAD researchers expected computation to rapidly empower designers to solve new problems algorithmically, and to challenge traditional design methodologies and modes of representation in architecture practice. To their dismay, chiefly from the middle part of the 1970's, it was 2D digital "hand-drafting" systems like AutoCAD that became far and away the most widely adopted and applied approaches to CAD. Rather than challenging the status quo for design practice, the emergence of digital drafting tools instead reinforced traditional models for design and project delivery. Such representational methods – which became nearly ubiquitous in architectural practices by the 1990's, and indeed which remain central to most contemporary design practices – were of the same sort that Nicholas Negroponte discussed in disparaging terms frequently in the 1970's. He had first warned against them in *The Architecture Machine*, suggesting that "computer graphics is not a synonym for computer-aided design. The significance of graphic interaction can be no greater than the meaningfulness of the content in the transaction. No matter how fancy and sophisticated the computer graphics system, it is only a glorified blackboard or piece of paper." And as CAD became most widely applied for just such a purpose, he responded with alarm in his introduction to Soft Architecture Machines, asserting that "[our current technological track is leading us toward] achieving efficient, financially secure, and structurally sound ways of building the same junk cheaper and faster, without devoting an equal measure of time to scrutinizing the design process itself." Even so, at this point it is important to note that, despite some of these early disconnects between the theoretical intentions of researchers into CAD and its actual developments in terms of both nature and adoption, several important aims were articulated during this time, related to such topics as algorithmic design and computer simulation, including one of the most central and enduring concepts that animates contemporary computational modelling practices originated from these early, research-focused implementations of CAD: the privileging and employment of computational thinking.

Computational thinking

A general and pliable definition of computation is that it embodies a "system of reckoning." Through an examination of the etymology of the word "compute," the physicist and philosopher Heinz von Foerster asserts that "[computation]…literally means to reflect, to contemplate (putare) things in concert (com-), without any explicit reference to numerical quantities." Computation then reflects any "operation, not necessarily numerical, that transforms, modifies, re-arranges, or orders observed physical [or symbolic] entities…" (von Foerster 1973) This perspective asserts a critical detachment of computational dependency from the digital computer, and it moves from being an operational descriptor toward being a specific mode of thinking that enables the productive synthesis of information. Naturally, digital computers are the instruments best suited to perform computation, but it is crucial to recognise here that computation refers not to an instrument but to an approach: computation does not require a computer. It has been suggested a computer need not be applied to computation, and instead may do something else entirely.

Today, the terms "computation" and "computerise" as commonly applied appear largely interchangeable, both associated with either the operation of or the operations performed by any of the multitude of digital instruments with which we interact on a regular basis. However, numerous researchers and theorists ascribe important differences between these two terms and have discussed them with an especial aim to ascribe epistemological separation between them. They place value on computation for its use in knowledge production and for its transformative potentials. This is contrasted with what is generally described as a "computerised" approach, which was perhaps first articulated by Negroponte, who framed the distinction as existing between "computerizedness" and "computer-aided". (Negroponte 1973) It was again by Kostas Terzidis, (Terzidis 2006) and more recently by Sean Ahlquist and Achim Menges. (Ahlquist and Menges 2011) According to these last authors – in definitions which draw on and aim to extend those from the previous works – "the distinction between computation and computerisation…can be broken down as methods which either deduce results from values or sets of values [computation], or simply compile or associate given values or sets of values [computerisation]. One increases the amount and specificity of information, while the other only contains as much information as is initially supplied." In this view, computation is fundamentally transformative as an information-producing exercise, while computerisation works as a static tool for collating or containing information that has been previously generated. The value system being supported here should be clear: that computational design approaches have a unique capability to improve design processes through richer, more productive modes of design thinking, whereas computerised models are inherently inert and non-productive relative to inventive design value.

The computer scientist Jeannette Wing defines "computational thinking" 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." (Wing 2006) Computational thinking is applied within a system of reckoning through the encoding and execution of algorithms as information-processing agents. Ahlquist and Menges talk more explicitly about how this type of thinking applies to design practice: "one critical aspect of working in a computational manner is the processing of information algorithmically [which means developing design systems that operate according to] a set of procedures consisting of a finite number of rules, which define a succession of operations for the solution of a given problem." According to this perspective, a computational design approach requires modelling setups that perform explicit transformative operations using algorithms in pursuit of a design outcome.

Contemporary computational design practice

Although the ambition for engaging in "computational thinking" for design has been clearly articulated since the inception of CAD over fifty years ago, these ambitions emerged in a context of computer scarcity, high expense, and limited power. While early researchers into CAD were certainly resourceful in their development and implementation of computational approaches and elicited sometimes astonishing results from their computational modelling systems, limitations in computing capacity as often led to computational design theory outpacing implementation. Indeed, it has proven to be decades before the "elbow" in the exponential growth curve associated with computational power has yielded performance improvements that allow for the testing of these theoretical frameworks, much less have them prepared for wider-scale application or broad implementation in practice. And because many of these early theoretical frameworks relied on the emergence of phenomena that have even today failed to materialise – such as more general machine intelligences – many of their initial ambitions have since been largely recalibrated. So, while an interest in computational design thinking has been a persistent feature of research into CAD since its inception, it took decades for its more advanced theories and the means for its testing and implementation to begin to approach each other in practice.

While there is no hard boundary defining a single moment when computing capacity became cheap and powerful enough to more thoroughly test or implement previously theoretical computational design modelling logics, for the purposes of this research project, I locate this convergence roughly at the turn of the 21st century. This timeframe is also coincident with the rapidly increasing emergence of specific tools and programming frameworks that have dramatically transformed the computational modelling landscape – increasing both the breadth and depth to which they may be deployed – and which is discussed in greater detail in following section titled "Autocatalytic development for computational modelling technologies." For this research project I will characterise both professional and academic researchers who have since that time located algorithmic or procedural modelling approaches central to their research or practice agenda as engaging in contemporary computational design practice. Among the practices that can be thus characterised, there exists some variety in the terminologies by which they self-identify their mode of engaging in design modelling processes. These terms include (but are not limited to): Parametric Design, Computational Design, Design Computation, Generative Design, or New Materialism. While there are some nuances that may differentiate some of these approaches, this research project more generally refers to these or other similarly termed practices for their employment of computational modelling methods.

1.2.3 Situation: the evolutionary nature of design technology

In this context of contemporary computational design practices, readers of this document will likely be aware that we are in the midst of a continuous emergence of new digital design modelling systems and tools, with increasing availability and ease implementation for computational modelling and design. The instruments borne of this phenomenon are simultaneously growing in both number and specificity of function, so we are seeing not only a greater variety of capabilities embedded in these tools, but also frequently multiple tools competing to perform the same functions. This is partly a result of the fact that many design platforms are themselves configured for further customisation and specialisation, and they endow designers with the ability to author their own software extensions and add-ons to more directly address distinct modelling problems. One consequence of this empowerment is then that the increases in both number and specificity of platforms and tools are observed to be at least partly autocatalytic in nature: modelling tools are built to facilitate the building of new tools. This potential for ongoing refinement within contemporary computational platforms then empowers designers to deploy complex mixtures of both invention and custom implementations for existing algorithms, supplying their modelling systems with a broad range of exploratory, generative, analytical, and descriptive potentials. In addition to these increases in potency and specialisation, however, there are several important and related implications for the explosive expansion of design technology, especially regarding challenges that contemporary designers face in effectively applying these instruments in practice. These qualities are here introduced not only in relation to digital modelling practice for architecture, but also as they reflect trends exhibited within the larger framework of general technology.

In *What Technology Wants*, the technologist and critic Kevin Kelly positions human-created technology as a broad, emergent, and holistic entity. It encompasses not only what we might casually consider to be technological – such as that which is physically made or engineered – but is directly linked to the human capacity for abstraction in both general and applied terms. So, technology includes not only the tools and instruments we make and use, but further is comprised of the linguistic and cultural frameworks that make their invention and manufacturing possible. Kelly considers these aboriginal components of human thinking and social construction as a natural extension of biological evolution, and ultimately argues that technology itself is then not only a natural extension of evolution – all human knowledge both abstracted and physically manifest– but is in fact governed by the same principles that do evolutionary biology. More than an analogy, he argues that technology exhibits continuously emergent properties that orient it toward self-organization, proliferation, adaptation, and both novelty and convergence. He asserts that it constitutes a "seventh biological kingdom." According to this position, technological evolution is thus endowed with the same actual characteristics of biological life in these crucial regards: just as life will evolve toward increasing complexity, variety and specialisation in any suitable ecosystem, so we can expect our technology to continue to similarly complexify, proliferate, and specialise, just as biological evolution does: our technology is growing in both abundance and variety. Interestingly, this proliferation results in the simultaneous production of new technology in two general directions. First, it produces new output that is more specialised and therefore varied in its function, what we understand as innovation. But second, it also leads to the creation of new instances of functionally similar – or convergent – manifestations. One important feature of Kelly's formulation of technology – and it applies to both the innovative and the convergent – is the inevitability of this continued evolution. Kelly provides examples that support different types of evidence for this, related to the facts "most inventions and discoveries have been make independently by more than one person," that in ancient time "we find independent timelines of technology on different continents converging upon a set order," and that in modern times "we find sequences of improvement that are difficult to stop, derail, or alter."

The aim in discussing Kelly's observations on the evolutionary nature of human technology is not to stake claims as to whether such a position is scientifically falsifiable, but rather to frame important concerns germane to the state-of-the-art in contemporary design modelling for the building sciences. Even tangential observers of digital modelling systems for AEC will be aware of the acceleration of changes they have undergone in their roughly fifty-year lifespan. During this time – like nearly all computer-based technologies – digital modelling hardware and software systems for the building sciences have gone from being both prohibitively expensive and vanishingly rare outside of either academic or commercial-based research institutions, to being increasingly powerful and cheap, such that they are now effectively ubiquitous in practice. What was once considered a novelty for many architects has become indispensable: it is almost unheard of in contemporary design practice for a building of even modest complexity to be designed and built without the use of extensive digital representation. For digital modelling systems within the building sciences, ample evidence at least supports the historical accuracy of Kelly's position, and strongly suggests its predictive strengths. It is safe to say that we can expect design technology to continue its emergent transformation, which will include it becoming at once more complex, specialised, and redundant.

Autocatalytic development for computational modelling technologies

It has been earlier noted that the turn of the 21st century roughly denotes an inflection point for CAD. While theoretical frameworks for CAD had previously been extensively developed and achieved a high degree of maturity, the ability for researchers and practitioners to rigorously test these frameworks had been somewhat limited by available computing power, data storage, and software platforms.

Moore's Law – which asserts a doubling of the density of transistors on silicon chips every two years – had been demonstrable throughout the history of computers. Similar growth rates are reflected in several other metrics related to computational power, such as for single-thread clock speeds, frequency, data storage, and power usage. The practical impacts of these exponential growth curves became increasingly felt in the field of CAD largely from the late 1990's, as computer hardware improvements and increased economic viability led to rapid advances in commercial software modelling platforms that were at once cheaper and vastly more powerful. So, some chief consequences for CAD researchers and practitioners in the emergence of these new platforms for hypothesis testing and investigation were: increased access to powerful and flexible modelling systems that afforded vastly improved capabilities to better engage long-standing theoretical questions; the ability to implement previously intractable algorithms or computational approaches; and improved means to identify and explore new theoretical frameworks.

Many of the new or improved software-based design modelling tools from this time were developed in such a way that directly supported an *autocatalytic* evolution of new computational design modelling platforms. In chemistry, autocatalysis describes a reaction whose catalyst is a product of itself; here, it refers to the production of new design modelling platforms as activated through the framework of existing modelling platforms, not related to the production of new versions, but rather as means by which users can enhance, extend, or further customise the existing software. There are two related features of many contemporary modelling platforms that have contributed to the autocatalytic evolution of computational modelling platforms.

The first of these is the availability of Application Programming Interfaces (APIs) and/or Software Developer Kits (SDKs) for many popular CAD modelling, analysis, or project delivery software platforms. APIs and SDKs empower users to gain access to a given software platform's underlying data structures and object-level transformational methods in ways not typically exposed through traditional user interfaces (UIs). Here, designers will use an Integrated Developer Environment (IDE) to write and execute programs that leverage the "core" tools of a software platform, but unbounded by UI constraints that have failed to anticipate certain design interests and may inhibit the application of recursive or iteration-based algorithms. Users will frequently write programs through IDEs that are either directly embedded in the base software platform itself, or work through standalone developer applications (such as Microsoft Visual Studio) that enable them to prepare and compile programs to execute within the software modelling environment. APIs and SDKs are frequently presented in accessible, "high-level" programming languages – such as C#, VB.NET, JavaScript, or Python – which make writing code more human readable, and therefore may be especially tractable for designers who rarely have extensive formal training in computer science. The importance of SDKs and APIs to contemporary design modelling platforms is underscored by their abundance: a short – and very incomplete – list of design modelling software packages that ship with APIs and/or SDKs include Rhinoceros 3D, Blender, Revit, MicroStation, Catia, Tekla, SolidWorks, and Navisworks. It is, in fact, difficult to find contemporary CAD platforms that do not in some way incorporate programmatic access for users to underlying data structures and object libraries.

The second feature supporting the autocatalytic development of design modelling platforms is frequently a consequence of or subsequent to the first: in addition to APIs and SDKs, many established modelling platforms now also provide integrated plug-ins for using Visual Programming Languages (VPLs). VPLs provide graphical interfaces that allow users to apply complex algorithms across the design supply chain without requiring any training in text-based programming. They most frequently use "node" and "wire" based systems that are configured as part of directed, acyclic graph, where each node represents an instruction set, and each wire represents the transfer of information either to an input or from an output parameter. While VPLs have their own steep learning curves, they are remarkable for their accessibility to people without programming backgrounds and are frequently recognised as supporting more intuitive exploration in design practice than text-based programming alone. A partial list of VPLs used for computational design modelling includes Generative Components for Bentley Architecture; Grasshopper for Rhinoceros; Dynamo for Revit; Sverchok for Blender; Houdini's operator-based structure; Marionette for Vectorworks; or the 3DExperience Platform for CATIA.

It is difficult to overstate the impact that these developments have had on both the advancement and the adoption of computational modelling practices within CAD. These tools enable inclined architects or engineers to customize and automate the modelling workflows already afforded by each software platform to design, specify, analyse, or otherwise produce design representations. Users can create their own programming libraries, using combinations of invention and implementation to investigate, develop and execute new or refined modelling workflows. Furthermore, they may integrate programming libraries that have been developed by others, even outside of a given software platform or framework. The potentials for recombination reflect the trends that Kelly outlines in *What Technology Wants*, as the emergence of new design technologies exhibit the same modes of proliferation, specialisation, and convergence seen across technologically-engaged industries.

Implications of inevitably evolving and complexifying design modelling technology

As Stan Allen states in *Architecture, Technique and Representation*, "buildings are both imagined and constructed from accumulated partial representations." For contemporary design practices, these partial representations are increasingly contained within or comprised of models that occupy related spaces within larger networks, with each individual model performing one or a series of specific functions or tasks for a given project. As previously discussed, we have seen a proliferation of broadly available modelling tools and systems resulting not only from increasing numbers of commercial modelling platforms, but also because of both text-based and visual programming environments that enable computational modellers to invent, extend, enhance, and customise workflows. This proliferation in turn leads to an increase in specialisation for modelling tools, such that more instruments of varied type and origin may be brought to bear on building projects across scale.

It follows then that these networks of partial models used for project development in contemporary design practice have also seen their constituent partial model elements increase in number, heterogeneity, and complexity. And the adoption of newer and more varied representational engines appears fundamentally irreversible: not only are we unlikely to cease use of existing extensions or specialised instruments, but we may inevitably see them continue to specialise and proliferate. Thus "unifying" approaches to modelling practices – those which would propose that we isolate, reduce or simplify the number, type, or function of the instruments we use for model development – are at a minimum becoming increasingly intractable, and will furthermore fail to capitalise on the improved design intelligence afforded by varied advances in modelling technology.

Here it is important to observe that contemporary architectural projects of even the most modest complexity invariably rely on multiple digital models for design; exploration; iteration and development; and ultimately project delivery. This notion of a "multi-model" or "network of partial models" has been previously identified and featured as a topic among many researchers for a variety of reasons, which include but are not limited to: interests in developing improved collaboration practices (Holzman, 2009), efforts to create systems capable of minimising information loss between models (Coenders, 2011), or a desire to effectively enhance each individual sub-model's design contribution to the project whole through efforts to activate the interfaces between them (Kilian, 2006). Model networks – and the importance of developing effective methodologies for formulating them and negotiating the information thresholds that bind their constituent partial models – will be explored in greater detail in Chapter 3.

1.2.4 Orientation: the ongoing crisis in digital design modelling

The importance of "computational design thinking" to contemporary discourse has been introduced, and some of the shared or more common characteristics attributed to practices engaged in computational modelling have been identified. But just as CAD and computational modelling technologies continue to increase in number, variety and complexity, it is observable that so do the discourses and critical concerns that surround them. These are noteworthy for the broad range of problems – and suggested modes of address – projected from these multiple perspectives. Yet despite this apparent diversity in contemporary theoretical discourse either directly focused on or related to design modelling, many of the positions taken frame the challenges facing practice as constituting some form of *crisis*. Each describes contemporary design approaches – and the modelling methods integral to them – as being fundamentally defective in some important way. Having first identified the fundamental flaws that create the crisis, each tends to respond with a specific approach as a solution, or, absent this, at least defines a set of theoretical criteria that should be met to ameliorate or overcome the condition that either has created or constitutes the crisis as described. Yet many of these positions in fundamental ways disagree with the others on both the nature of this defectiveness and effective means to address it. This subsection briefly introduces multiple relevant examples of this tendency to describe contemporary architectural design modelling as existing in a state of crisis, with an especial focus on the differences that exist between them.

The aim in presenting a short survey of some of these positions here is partly to highlight their variety, as well as their frequently contradictory nature: what constitutes a crisis for one observer may fundamentally be at odds with that defined by another. More importantly, the goal of this section is to present these diverse understandings of crisis as it parallels the accelerating proliferation of available technologies for design modelling and production described previously. It is natural that if design modelling systems are inevitably becoming increasingly varied in their form and function, that criticism of their utility or underlying value should become similarly varied. The goal here is to establish a basis for the development of an alternative framework for modelling theory and methods that responds to the increasingly heterogeneous nature of both problem and solution states raised in contemporary discourse. Ultimately, a case will be made for a more inclusive understanding of these crises, one that embraces a more flexible and inclusive understanding of both modelling challenges and the means to address them, effectively embracing the difference that is embedded in this increasing variety.

The Divorce of Form from Matter

In her 2010 thesis *Material-based Design Computation*, Neri Oxman describes a "crisis of form" as the key point of departure in her research motivation. She argues that contemporary architectural design practice is plagued by a long-established and ongoing trend toward the systematic divorce of material consideration from form-making processes. She further asserts that the emergence of advanced computational tools for architectural modelling has – at least in professional practice – both accelerated the rate of this division and exacerbated its consequences: their usage endows designers and engineers with the ability to more easily express complex, mathematically-driven forms in a purely digital, abstracted representation. While this outcome is itself not necessarily problematic, these same tools have allowed architects and engineers to resolve the necessary assembly details and structural specifications that allow for the forms to be realized as built objects, but without a suitable re-examination of the underlying material concerns embodied in the systems assemblies. In effect, contemporary tools allow for more traditional assembly methods to be applied to complex geometry. For Oxman, these are not welcome developments, and she is critical of their implications to practice, asserting that "[while] these new design spaces [afford] much liberation in terms of formal expression...[they have] also broadened the gap between form and matter and made the hierarchical and sequential separation of modeling, analysis and fabrication processes infinitely more pronounced." (Oxman 2010)

For Oxman – and many others as well – the absence of fundamental dependencies between a designed artefact's formal logic and its composite material assembly is deeply problematic for architectural design. Her practice is directly engaged in making material behaviours central to both the modelling and morphogenesis of her design systems, and so her agenda is understandably thus oriented, and she builds much of her discourse within a biological or biomimetic paradigm.

Tools with nefarious agendas

With a background in both architecture and psychology, Bryan Lawson has since the 1970's focused on design thinking, knowledge production within and through design, and the methods through which architectural design is formulated and deployed. A topic of great interest for Lawson is the central role that drawing and representation play in the generative aspects of design: "the modern designer… experiments not with the object itself but with representations of it." (Lawson, 2004) He consolidates the notion that ideation and invention are supported by drawing and enumerates many of the specific types of drawing that animate and further design processes, offering a detailed "taxonomy" of representations according to their function and composition. In addition to their variety of purposes, the mode of production for representation is important to Lawson: "the medium through which a designer represents thought is central to his or her work process." (Lawson, 2002) In this context, he identifies CAD systems and methods as presenting uniquely limiting challenges or constraints for designers. Lawson is unsparing in his criticism of work authored through digital means:

> *"Why is the work itself so bad? Is it possible that we have failed to notice that such CAD systems are not neutral in this process, but that they actually encourage poor design? Of course, the software cannot intend anything, and certainly the developers did not intend such*

results, but the effect remains."

For Lawson, the legibility of the computer as the instrument for design in the final product reveals an absence of a fundamentally important type of control on the part of the designer: "what is of concern is that the computer system, rather than a person with a philosophical position about architecture, is setting the design agenda." (Lawson, 2002) Lawson suggests that for a CAD system to truly become an "aid" to design, it must facilitate the transfiguration of design ideas from concept to representation in ways that it has heretofore failed.

Black boxes and intuition killers

In 2009's *Simulation and Its Discontent,* Sherry Turkle reviews (largely through her own observation in academia and and professional practice) the turbulence that has surrounded advances in computational design technology. Her observations especially follow the experiences of practitioners who have participated in the transition from a 2D-focused "hand-drawn" design method into the more wholly digital systems that are used in contemporary practice. She suggests that focusing on those who have at different times relied chiefly on both analogue and digital representational methods affords valuable insights into what may have been lost or gained during the transition. Turkle uses the term "simulation" broadly, considering it inclusive of simple, digitally situated 3D models; high-resolution visualisations or renderings that aim to describe materiality; or advanced structural analysis systems. (Turkle et al., 2009) While each of these ways of applying digital simulation presents its own set of challenges, for Turkle they share an underlying problem in that they cultivate a "visualization/reality blur," whereby artefacts observed in a digital environment can convey a sense of reality to a designer that is unverifiable, or non-contextual. This "blur" operates as a type of "black-box" that houses analytical logics and developmental processes that designers had previously maintained more directly and empirically, as sets of either internally cultivated intuitions or heuristics that could be both learned shared; more importantly, however, these heuristics reflected a deeper understanding of the underlying processes and forces that guide and inform well-executed design. Through the computer, designers either lose their memory of these important intuitions, or never acquire them to begin with, and therefore lose crucial understandings of both design problems and the mechanisms to address them. So while computer-aided design may extend the types of representations and analyses a designer may have available, it may being doing so at the expense of expertise, and undermining its own potential for increased utility.

Supply chain disconnects

Roughly mirroring the evolution of computational modelling during the early part of the 21st century has been the adoption of Building Information Modelling (BIM) as an instrumental modelling approach that supports project delivery, collaboration, and coordination within and across the architecture, engineering and construction industries. BIM's more widespread application in professional practice draws on the same trends that have enabled the rapid transformation of computational modelling technologies, as its adoption has been made similarly tractable according to the increased availability of cheaper, more powerful computers and more advanced modelling software.

A primary animus for BIM adoption – and a chief problem space it defines and seeks to address – stems from a desire to address the tensions that are produced when advances in design technology are implemented asymmetrically or adopted incompletely. Chuck Eastman has had a leading interest in CAD development, from the solid modelling systems of the early 1970's up through the most current BIM software platforms. In the 2011 edition of the BIM Handbook he writes that "currently, the facility delivery process remains fragmented [because it depends on] paper-based modes of communication," whose "errors and omissions" lead to "unanticipated field costs, delays, and eventual lawsuits between the various parties in a project team." Despite efforts "such as the design-build method; the use of real-time technology, such as project Web sites for sharing plans and documents; and the implementation of 3D CAD tools," little has been done to "reduce the severity and frequency of conflicts cause by paper documents or their electronic equivalents." (Eastman et al. 2011). This presents a condition wherein project stakeholders are expected to duplicate efforts: on the one hand, "model-based" project delivery is prioritised, but requirements for maintaining traditional drawing sets persist. The proposed solution is at least partly toward the homogenisation of the modelling environment: by centralising design and production models into more uniform frameworks, these inconsistent or redundant requirements may be addressed.

Competing claims

What seems obvious according to each of these positions for computer-based architectural modelling is that architectural practices are suffering from an ongoing crisis of modelling. Yet the crisis is variable in nature, the (incomplete) list above suggesting, for example, that it is either: one of an absence of applied material intelligence; or one of failed efficiency in coordination and collaboration; or of alienation between designer and requisite design knowledge; or of fundamental failures in the tools themselves to support processes of invention and discovery. Despite these differences, however, each perspective appears to agree that technological innovation for CAD (and its role in producing representations for design, development and project development) is both a generator and product of continual disruption. In *What Technology Wants*, Kevin Kelly discusses this key quality in technological development: that while many emergent technologies are introduced to solve specific problems, they almost invariably introduce new problems of their own. In this context, the development of modelling frameworks and methodologies that both recognise and aim to adapt to this perpetual trubulence in both the challenges and opportunities afforded by continuous technological advancement seems a desirable goal.

1.2.5 Point of departure: fractures and opportunities

This chapter section has described some key concerns whose synthesis provides a point of departure for the research questions and interests that animate this thesis. Within the context of CITA's broader *Complex Modelling* research project – which critically engages with contemporary modelling practices by questioning established information structures – these are:

1. That computational modelling techniques are uniquely qualified to confer specific types of value for project design, development and delivery through the generative, analytical, and descriptive potentials afforded through algorithmic transformation.

2. That the technologies through which we can engage CAD and computational modelling are following an irreversible trend toward increased complexity, variety, and abundance, and in important ways are therefore at risk of becoming similarly fractured or disconnected. This risk for disconnection is especially problematic in light of the fact that the same trends are increasing the number and variety of partial models that now invariably used in tandem for project design, development and delivery.

3. That contemporary discourse frequently addresses or understands this ongoing evolution in a framework of crisis, but that it does so in a similarly fractious manner: with sometimes contradictory

> interpretations of the problem leading to similarly contradictory proposed solutions or theoretical criteria for redress. Considering that the variety of digital modelling typologies – both in technique in theory – is itself increasing at a rapid rate, then this ongoing dissonance is itself at risk increase over time.

1.3 Conclusion and thesis structure

Already more than twenty years ago, Tom Maver admonished the CAAD futures conference that "it [was] almost impossible to find a PhD thesis which claims anything less than an all-singing, all-dancing, fully integrated multi-disciplinary design decision support system which does the business as soon as you press the start button." (Maver 1995) While this position may reflect some rhetorical exaggeration, it warns against adopting rigid, limiting, or exclusive and ultimately counter-productive ideological frameworks. Especially considering the previously described increasing diversity in both available design modelling instruments and methodologies, this scepticism toward any sort of claims to a singular digital modelling panacea seems well-placed.

It is worth noting that contemporary modelling frameworks may indeed be in a state of ongoing crisis. Despite claims of ownership from different positions, it seems most likely that this crisis is multi-faceted in nature, not unlike the makeup of contemporary modelling systems and model networks. This research project therefore suggests an alternative methodological approach that aims instead to be more fundamentally inclusive: it considers model diversity itself a target of epistemological interest, and privileges methodologies that focus on the formulation of model networks that can better elicit improved performances from constituent partial models explicitly based on this diversity. While it does consider this out of necessity – the proliferation of new design systems and modelling frameworks is undergoing continual complexification within broader technological trends – it more importantly engages in it cognisant of the opportunity embedded in increasingly specialised systems to produce better intelligence for target design systems. In addition to the greater descriptive potentials embedded in increasingly powerful modelling systems, however, this understanding of partial model diversity must also address new challenges introduced through the increasingly complex organisation of model networks that implement them.

In support of this aim, this project has experimentally and discursively engaged the information thresholds, or parameter spaces, that exist between partial models with broader model networks. This chapter has introduced adaptive parameterisation as a process by which these constituent partial models may engage with and more effectively enhance global performances, ultimately to encourage or facilitate open-ended design practices that support a range of functional activities across the project supply chain. This methodology has been described as strategically conjunctive, in that it aims toward inclusive approaches to model formulation which both recognise and seek to advantageously exploit model diversity.

This chapter has also introduced a series of research interests – or vehicles of inquiry – that have provided important interfaces with existing discourse, theory or instrumental approaches, and have helped animate the experimental content of this research project. These include *open topologies*, *design simulation*, *understanding agency as a continuum*, *machine learning*, and *multi-scalar modelling*. Each of these interests will be discussed in the context of their direct experimental applications within both the publications presented as the principle content of this dissertation, as well as in the next two chapters, which help further frame the methodology, argumentation, and theoretical context of this research project.

Structure

This thesis is divided broadly into three parts. Part I is comprised of three chapters, the first of which is the introductory chapter you are now reading. The second chapter in the first segment is titled *The digital-material practice*, and it presents the methodology used for this research project. This describes an approach to research-through-design that considers the design experiment – in both implementation and broader interface with theoretical discourse – as its central feature. This methodology is further articulated as a broader method for reflective practice and is presented as an important contribution for this research project. The third and final chapter in Part I presents a theoretical context and state-of-the-art for the research project, defining in greater detail the instrumental and epistemological nature of model networks. In so doing it focuses on their fundamentally ecological nature. It examines holism and general systems theory as a means to consider the variable implications that different approaches to partial model formulation – both intrinsically, and especially as they relate to one another – may have on a model network's performances. In support of this, it explores the data structures that comprise the parameter spaces that act as information thresholds between partial models.

Part II is comprised of a selection of peer-reviewed publications that constitute the main body of this dissertation. These are largely, but not exclusively, related to specific experiments that have been undertaken as the principle mode of inquiry for this research project.

Part III includes a brief conclusion that aims to synthesise the findings of the experiments presented throughout Part II with the theoritcal framework outlined in Part I. It offers some final thoughts to further contextualise this projects contribution to practice, as well to discuss shortcomings and opportunities for future work.

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2. Methodology: The Digital-Material Practice

This chapter articulates the methodology for this research project. It presents an investigative framework that has, through an integrative process, identified, explored, expanded and adapted its arguments. This framework pursues an iterative series of active, design-driven engagements with complex modelling for architectural practice, which support the development of ontological and epistemological interests associated with and required for defining an approach toward model formulation and implementation practices. This process engages in the sequential and accumulative conceptualisation, development and implementation of complex digital design models, and correspondingly informs knowledge production through practices of representation, synthesis, and dissemination. This reflects that this PhD project has been developed within an experimentally-driven architectural research practice, pursuing knowledge production through a recursive integration of making and reflection. It engages in the ongoing (re)formulation of problem spaces encountered or identified in architectural practice and considered relevant to advancing the state-of-the-art.

2.1 Research through design

"Research through design'" is a methodology for engaging in design research. It has been explicitly articulated in a 1993 working paper by Christopher Frayling, where he defines research through design (in contrast to research into design and research for design) as being enacted through an engagement in either: materials research (to create or modify a design-relevant material to better effect); development work (to customise a piece of technology either to improve it or allow it to support a different goal); or action research:

"A research diary tells, in a step-by-step way, of a practical experiment in the studios, and the resulting report aims to contextualise it. Both the diary and the report are there to communicate the results, which is what separates research from the gathering of reference materials." (Frayling 1993)

This mode of pursuing design research as an action-oriented, creative practice is a broadly accepted methodological framework employed across a wide range of design fields. As of 2011, Koskinen et al. suggested that understanding of the term had even indeed become overloaded with competitive claims, and importantly failed to account for alternative types of design-driven constructive knowledge production that didn't involve physical artefacts. In response, the authors propose that an alternative term for research through design is necessary, which they term "constructive design research," which:

> *"refers to design research in which construction – be it product, system, space or media – takes center place and becomes the key means in constructing knowledge. Typically, this 'thing' in the middle is a prototype… However it can also be a scenario, a mock-up, or just a detailed concept that could be constructed.'" (Koskinen, Zimmerman, and Binder 2011)*

Research through design explicitly couples design artefact production with knowledge production, with the important requirements that the experimental processes be logged, and the results contextualised, reflected upon and disseminated. Such an approach is similarly described by Stan Allen as a "material practice," which he defines in Practice: Architecture, Technique + Representation:

> *"Material Practices… involve operations of translation, transposition, or trans-coding of multiple media. Although they work to transform matter, material practices necessarily work through the intermediary of abstract codes such as projection, notation, or calculation. Constantly*

mixing media in this way, material practices analyze the present in order to project transformations into the future" (Allen 2000)

Allen develops the idea of the material practice in contrast to what he terms a purely hermeneutic or discursive practice, which he associates with critical interpretations of theory, and which is characterised by its reflective nature, "[working] in the space between texts, [producing] more texts.'" Allen uses this notion as a foil in taking the position that architectural practice is more productive for theory-making and knowledge production exactly when it is "insistently affirmative and instrumental," dynamically engaged with design work and the production of the "real." The operative difference here is simple, and robust: material practice exerts influence and produces theoretical meaning through action. It engages with a "messy" and "stubborn" reality and achieves "practical (and therefore provisional) unity inferred on the basis of its ensemble of procedures."

The question of what exactly comprises the "material" component of the practice is not answered directly. Koskinen et al. had suggested that the designed artefacts – the products of Frayling's "experiment in the studios" – need not necessarily be physical in nature, only that they need to be produced through constructive design practices, and indeed may be entirely conceptual in nature. While the physically substantive qualities of the built environment and its relations to architectural practice are contained in Allen's conceptualisation of a material practice, the scope of this definition – especially in his reference to "abstraction" realised through "mixing media" – makes clear that it has been developed through an understanding of materiality that is not bound by the more traditional association of the term with the properties of exclusively physical matter. Here its more flexible nature is implicitly built up through a focus on the centrality of action, strategy, and the production of performative representations. We can look elsewhere for a means to develop a corresponding definition of materiality that suits these considerations.

2.1.1 Digital material practice

In *Digital materiality? How artifacts without matter, matter*, Paul Leonardi argues that technological innovation is fundamentally reframing how researchers into organisational sciences consider materiality. He refocuses the idea of materiality from what an object is – its composition as physical matter – instead to what an object itself describes. He asserts that when:

"…researchers describe digital artifacts as having 'material' properties,

> *aspects, or features, we might safely say that what makes them 'material' is that they provide capabilities that afford or constrain action." (Leonardi 2010)*

This argument contains two important features. First, it is reflective of Allen's instrumental understanding of the material component in practice: that it is directly connected to an engagement in action-oriented production. Secondly, and critical here, Leonardi expresses this through an evolving understanding of non-physical artefacts as possessing nonetheless explicitly material consideration. In his view they are afforded their own particular substance in the form of both "practical instantiation" and "significance." While the fact that he is formulating his argument relative to the production of digital artefacts, it is even more important in its abstraction of the notion of materiality, which is gained not through its matter but through a construct's performativity.

This resonates with Allen's similar decoupling of his understanding of the "material" from purely matter-based considerations, which he suggests by referencing the "calculative" nature of the "abstract codes" that are considered substantive products in the practice methodologies he privileges. Interestingly, writing at the turn of the 21st century, Allen's formulation of material practice coincides with the "inflection point" identified in the introduction that roughly delineates contemporary computational modelling practice. Since this time, professional and research-oriented theoretical discourse has made computational modelling practice a topic of inquiry for the very broad range of opportunities and constraints afforded by its attendant, expanding variety of increasingly sophisticated instruments. More importantly, these digital systems have been developed as theoretically integral components for exactly the type of action-oriented, reflective practices that Allen privileges, and are delineated by a continuously evolving framework in the development of state-of-the-art operational deployment techniques, conceptual foundations, and theoretical reasoning.

This research project then identifies an explicitly *digital-material practice* as a vehicle for the pursuit of these theoretical concerns, where the orientation toward action ascribed to materiality explicitly considers the ontological and epistemological importance of digital instrumentation, artefact production and methods and means of representation within contemporary architectural practice. A chief feature of a digital-material practice is that it pursues knowledge production through action research – as in research through design or constructive design research – with recursive interdependencies developed between making and reflection. The relationship between these two processes can be understood as an emergent, catalytic interface that is differentially activated, specific to individual research questions and their attendant hypotheses. Through design-led investigations into different research questions, digital-material practices may then incrementally suggest, reveal and produce the conceptual and analytical devices that facilitate the synthesis of artefact production with research findings for the advancement of theoretical interests and the state-of-the-art.

2.2 Experiment in research practice

Research through design – identified as the primary vehicle through which this project has been undertaken – centrally features the design experiment for the investigation, development and testing of both instrumental and theoretical knowledge. An "experiment" is defined in the Oxford English Dictionary as "1. A scientific procedure undertaken to make a discovery, test a hypothesis, or demonstrate a known fact, or 2. A course of action tentatively adopted without being sure of the eventual outcome." While both definitions suggest that experiments support action-oriented inquiries, the first suggests that their role is more closely tied to interrogating an existing theoretical framework. Indeed, several philosophers of science have asserted that the role of a scientific experiment is useful almost exclusively either to support or falsify theories or hypotheses that have been developed independently of empirically observed phenomena. Yet the second definition suggests a much more exploratory approach, whereby an action is taken without a clear expectation of its outcome. For practices interested or engaged in experiment, this tension – between the idea of experiment as a mode of exploratory investigation versus its role as an instrument more strictly used to test established theoretical frameworks – merits examination, especially within the broader field of design-based practice.

2.2.1 The role and nature of experiment

The influential philosopher of science Karl Popper developed and articulated the "critical rationalist" view of scientific knowledge, which came to be highly prevalent during the second half of the 20th Century. This perspective emerged as a response to both the rationalist and empiricist traditions, especially regarding "observationalism – the idea that we know about the world because we look around, open our eyes and ears, and take down what we see, hear, and so on; and that this is what constitutes the material of our knowledge." (Popper 1963)

Regarding scientific inquiry, Popper was particularly concerned with theory building, and argued that scientific practice was only legitimate in relation to its successful engagement with it. He established three criteria for determining the viability of scientific knowledge creation: 1. that the theory posited "should proceed from some simple, new, and powerful, unifying idea about some connection or relation," 2. that it "should be independently testable," and 3. that it "should pass some new, and severe, tests." From this perspective, he stringently argued that experiment should operate exclusively in support of this last demand: there is, in his view, a uni-directional movement of idea and motivation, flowing from theory to experimental practice. Central to this notion are two key features. The first is that theories are built according to deductive reasoning: working from given knowns, a theory will make a claim that is logically dependent on that established knowledge. Secondly, and crucially for logical positivism, the theory must be falsifiable. According to this view, if a condition cannot be established that may demonstrate the theory as incorrect, the theory itself must be non-scientific in nature.

For the role of experiment, then, Popper then explicitly refuted the "commonly held misunderstanding about empirical epistemology… that knowledge derives from observations rather than the other way around" with the assertion that "there are in principle an infinite number of different explanatory theories that can fit the observations" of phenomena, and therefore no meaningful conclusions can be derived from ungrounded material investigation. (Persson 2011) For Popper, experiment is "always performed to answer a question or to test a conjecture which has been posed by a theoretician." (Arabatzis 2008) This strict definition of experiment to test a hypothesis related to an established model or theory defines its application as a purely evaluative rather than generative enterprise.

Among both its practitioners and philosophers, there is a consensus that the development and evaluation of theories comprise a central pursuit in the natural sciences. However, the means for engaging in this pursuit remain a topic of interest and diverse opinions, and several concerns with the narrow view on the epistemology of scientific knowledge held by critical rationalists have been articulated. For example, Christopher Frayling is concerned with critical rationalism based on its idealism toward a purely theory-driven and deductive methodology, which he suggests are at best delusional and at worst intellectually dishonest:

> *"The saints have a self-evidently 'scientific' way of thinking, they tend to say 'Eureka!', and their successes instantly persuade the scientific*

community around them of the wisdom of their ways. It all seems so simple. And yet, of course, critical rationalism, which relies on making everything explicit, by revealing the methods of one's logic and justifying one's conclusions, and which has at the heart of its enterprise a belief in clarity, has been under considerable theoretical attack in the last 10-15 years… In Science – as in everything else – there may well be conjectures but many of them are unconscious and they tend to be changed or modified without any explicit discussion, and they tend to involve a significant measure of subjectivity." (Frayling 1993)

Imre Lakatos, a philosopher of science and mathematics, has specifically identified and been critical of what he argues are prohibitively limiting features encoded in Popper's epistemological insistence on falsification:

"Within a research programme a theory can only be eliminated by a better theory, that is, by one which has excess empirical content over its predecessors, some of which is subsequently confirmed. And for this replacement of one theory be a better one, the first theory does not even have to be `falsified' in Popper's sense of the term. Thus progress is marked by instances verifying excess content rather than by falsifying instances; empirical `falsification' and actual `rejection' become independent. Before a theory has been modified we can never know in what way it had been `refuted', and some of the most interesting modifications are motivated by the `positive heuristic' of the research programme rather than by anomalies. This difference alone has important consequences and leads to a rational reconstruction of scientific change very different from that of Popper's." (Lakatos 1970)

Here Lakatos is exploring the construction of "Research Programmes," which he defines as conceptual frameworks – or paradigms for a field of inquiry – that contain theories and modes of their development within them. Most relevant for this PhD project is the role that Lakatos asserts "positive heuristics" play in the development of new knowledge. In *A surrogate for truth*, Ian Hacking synthesises Lakatos:

"The falsificationist [such as Popper]… demands not that the theory should be consistent with the evidence, but that it should actually outpace it… By and large inductivists think that evidence consistent with a theory supports it, no matter whether the theory preceded the evidence or the evidence preceded the theory. More rationalistic and deductively oriented thinkers will insist what Lakatos calls… 'the

requirement that the – well planned – building of pigeon holes must proceed much faster than the recording of facts which are to be housed in them.'" (Hacking 1983a)

Especially consequential to the construction of new theories, Lakatos here is critical of the notion that relevant new knowledge can only be produced through metaphysical processes of theory formulation advocated by Popper. The implication raised by Lakatos and Hacking is that alternative means – both inductive and empirical – may be employed to create such "facts" which may (or may not) only ultimately be "housed" in a theoretical framework at a later time. Experiment as a form of rigorous and closely examined exploration may then be used to uncover or identify new theoretical insights. Prior to the advent of critical rationalism, such perspectives were non-controversial, and so in a strong sense they operate within well-established empiricist traditions.

Ranulph Glanville has expanded on this idea. A chief interest in this research project lies in the arguments he makes toward enabling experiment as central to investigation and theory formulation, similarly refuting the more hegemonic assertion of critical rationalism that denies experimental practice as an empirically-driven, exploratory enterprise that pursues inductive means to produce or investigate new knowledge. To be sure, Ranulph Glanville has a clearly derogatory view of Popper, caustically describing his "ideal" linear dependencies between theory and testing as being "impossibly ambitious for mere humans." Glanville alternatively asserts that any "relationship between theory and experiment is essentially circular," (Glanville 1999) positioning the instrumental role of experiment as being equally viable for either exploration or investigation as it is for evaluation, and echoing the position earlier articulated by Ian Hacking, who contended that experimental practice need not even have any direct ambition to either support or falsify of theory, only that it not operate entirely independent of theory. (Hacking 1983b). Theodore Arabatzis synthesises Hacking's perspective specifically as being broad in its allowances: "experiment should be concerned with the design, construction, and running of experimental setups which reveal or produce phenomena in a reliable manner." (Arabatzis 2008)

Allan Franklin has similarly articulated an expanded set of potential roles for experiments in scientific research, which similarly deviate from Popper's orthodoxy and further highlight and clarify the value of experiments as instruments for the types of empirical inquiry that Lakatos, Hacking and Glanville advocate. (Franklin 1986) Franklin claims that experiments may "have a life of their own" where they operate completely "independent of high-level theory." (Franklin 2015) To support this, Franklin enumerates several potential roles for experiment, establishing a typological variety for their uses that may be arrayed along an axis generally denoting both the type of reasoning that each instance of experiment supports – from the deductive to the inductive – and the functional nature of the experiment's relationship to the scientific hypotheses and theories – from the evaluative to the productive, and ultimately to the generative or exploratory. It is important to reinforce that these refutations of critical rationalism by no means deny that theory may not be deduced from prior knowledge or that experiment may be used to falsify or support it, but rather that such a view does not hold a strict hegemony over any such schema related to theory and experiment. What emerges is an understanding of experiment for the natural sciences taking on a striking typological diversity, related to both the testing of existing theoretical models and hypotheses, to the investigation of phenomena of interest, and in the production of new knowledge. I will aim to show here that understanding this variety is useful for the formulation of complex design models within a digital material architectural research practice.

2.2.2 Scientific design and design science

The epistemological concerns that produced this typologically heterogeneous understanding of the role of experiment have largely been raised in relation to their role in the natural sciences. In the context of material practices engaged in action-based research into complex modelling for architecture, it becomes important to explore some of the ontological and epistemological concerns that both unify and distinguish the natural sciences from design practice.

Ranulph Glanville identifies a critical concern for design research in his observation that, from its inception – and in relation to the natural sciences – the field of design research has considered itself a "second class subject." And for Glanville, design has mistakenly done so: it has characterised itself as being hindered by an intrinsic subjectivity, and therefore manifesting a paucity of intellectual substance, especially in contrast to the harder, natural sciences. He objects to this perceived (self) denigration of design research as an incorrect reaction to a "falsely elevated view" of science, and is dismissive of the apology it implies. He suggests an inversion of this power structure, claiming that rather than have designers aspire to post-positivist ideals of scientific objectivity, the natural sciences should instead be considered first as fields of design. He argues that the circular relationship between theory and experiment – comprised of devices for "simplification" and "pattern finding" and “of continuous modification and unification” – is foremost a “design process.” (Glanville 1999) For Glanville, scientists therefore work principally as designers, and therefore “(scientific) research should be judged by design criteria, and not the other way around.” Science is a “subset of design and not the other way around.”

While Glanville makes a strong case for central role design plays in the natural sciences, he also acknowledges that: “there are qualities essential (and all too often forgotten) in design which are remembered and given primacy in (scientific) research, such as rigour, honesty, clarification and testing, and the relative strength of argument over assertion.” So, if natural scientists are designers whose decisions don’t necessarily follow the rational logics they contend, then at least their experimental practice-based targets of interest command a particularly exacting set of constraints, related to measurability, repeatability, theory-making, and numerical precision. It is then more accurate to clarify that while the natural scientist is in fundamental ways also a designer, the converse is not necessarily true. But even this is a strong foothold for designers – and design researchers – to begin to understand their practices along a similar spectrum that delineates multiple functions, intentions, and methods of knowledge creation and evaluation that are central to the natural sciences.

In *The Sciences of the Artificial*, Herbert Simon proposes an approach that supplements Glanville’s argument for science existing within the domain of design, describing a “science of design.” Simon first defines what he considers a fundamental epistemological distinction between the interests of the natural sciences and design practices:

> *“We must start with some questions of logic. The natural sciences are concerned with how things are. Ordinary systems of logic, the standard propositional and predicate calculi, say serve these sciences well. Since the concern of standard logic is with declarative statements, it is well suited for assertions about the world and for inferences from those assertions. Design, on the other hand, is concerned with how things ought to be, with devising artifacts to attain goals.” (Simon 1996)*

Simon frames this through a key question that seeks to build a more unified understanding of the two apparently discrete pursuits: “We ask whether there cannot also be ‘artificial’ science: knowledge about artificial objects and phenomena.” The natural sciences may here be generally understood as primarily engaged with analytical and descriptive processes that employ deductive reasoning, as suggested by such perspectives as discussed earlier regarding critical rationalism. In this view they are concerned with theory building and testing – developing fundamental understandings – regarding the observation and description of natural phenomena, systems, and the laws that govern them. Simon points out that designed – or artificial – objects must obey these same laws that govern the natural world, but that their purpose is fundamentally different in their aims to effect change in the natural world through the instrumentation of goal-seeking functionality and operation. Designed artefacts can thus be understood "symmetrically:"

> *"An artefact can be thought of as a meeting point – an 'interface' in today's terms – between an 'inner' environment, the substance and organization of the artefact itself, and an 'outer' environment, the surroundings in which it operates."*

Design practice is then "centered precisely on [the] interface between" these two. Sciences of the artificial are fundamentally "concerned with… the way in which that adaptation of means to environments is brought about." Simon goes on to demonstrate that design processes that are sufficiently clear may be open to optimisation such that their "inner environment" can be calibrated to enact within the "outer environment" an outcome – or even set of outcomes – that may produce a measurably optimum output(s) regarding the design system's behavioural goal(s). Such design systems may then be developed through deductive reasoning: "the logic used to deduce the answer" to "the optimization problem, once formalized" is the "standard logic" of a mathematical system. But there remains at least one further consideration, that design practice is more often concerned with problems – or rather, problem spaces – that may not easily engage this framework for optimisation. These conditions are especially important within architectural design practice – and here especially as it relates to digital modelling method and theory – as it engages with such problem spaces and performance criteria that are well-documented for being inherently broad in scope, varied in type, and even self-contradictory in nature.

In T*he Reasoning of Designers*, Horst Rittel identified these particular qualities as being reflective of the management and reconciliation of a collection of "wicked problems" that are endemic to design disciplines. (Rittel 1988) These compound problems continuously evolve in response to insights and discoveries made through design investigation. Importantly here, they also "elude reduction" in such a way as to effectively eliminate the possibility for optimisation in all cases. This complexity in the multifaceted natures of target problem spaces is set apart from the types of complexity that attend many of the problems experimentalists in the natural sciences seek to solve, and even the means of measurement and goals of performance pursued for many engineering design problems. Furthermore, in addition to different components within a single problem space for design often being contradictory, they are also frequently difficult to measure objectively. Nonetheless, even under the conditions of it being intractable to identify any best solution, there remains an aim to formulate solutions that may be better than others. Herbert Simon identifies a particular type of design solution that may not be optimised (or even be able to be optimised) but may instead reflect rigorous effort toward an improved (or "satisficing") solution for a given problem space. This introduces an important evaluative criterion that affords for relative rather than absolute performance improvements. And even in the rare case where a multi-faceted design problem may theoretically be optimised, Simon suggests that tractable searches of the problem space nevertheless demand a move from deductive approaches – which is here formulated through "brute force" calculations of each permutation in the problem space – toward inductive reasoning, using observational experience and iteration to formulate methods for performing effective heuristic searches that support better, "satisficing" design solutions. Simon formalises this aim by declaring that the artificial sciences are then interested in "two central topics" which relate, where possible, to the "body of techniques for actually deducing which of the available alternatives is the optimum" and alternatively to a "decision theory as a logical framework for rational choice among given alternatives."

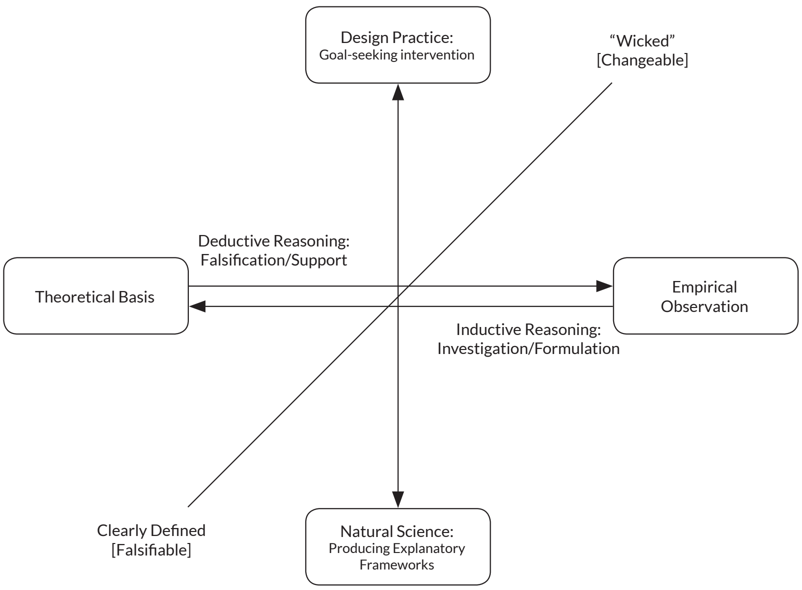


Figure 1: Diagram describing the axial relationships between reasoning types, the base interests between the natural and design (or artificial) sciences, and types of problems presented in practice.

These two chief modes of reasoning that define the natural sciences and the design sciences may be expressed as logical processes that move in opposite directions: inductive reasoning moves "from the observation of specific instances to the formulation of general laws" (Archer 1995) whereas deductive reasoning begins with premises deemed to be true, and through their integration makes a declaration that necessarily follows. Deductive reasoning is most often used to support theory or hypothesis testing, or to perform exhaustive searches of measurable values to identify optimum values. Inductive reasoning is most often used to interpret phenomenological observations to develop explanatory frameworks, or to formulate methods for heuristic searches of complex problem spaces with either contradictory or difficult to measure optima. Different mixtures of these modes of reasoning are then applied (whether acknowledged or not) in the formation of both types of practices explored here. These mixtures become important when developing an understanding of the types of experiments that will be most productive for pursuing a specific problem, whether it is more purely scientific, or more generally design-oriented.

2.2.3 Locating experimental practices

In consideration of these parameters, an understanding of the natural and artificial sciences as being very much enfolded within each other emerges, keeping in mind an important distinction between the two discussed earlier: that goals for intervention enacted through design practice are fundamental to the pursuit of natural sciences that engage with theory through experimentation, but that the converse is not necessarily true, and natural sciences are not explicitly fundamental to experimental practices in the design sciences. And yet, it is also apparent that, because the "the peculiar properties of the [designed] artefact lie on the thin interface between the natural laws within it and the natural laws without," those laws should inform as much as possible the "logical frameworks" (Simon 1996) that are pursued through the artificial sciences. Many engineering practices exemplify this overlap: their principal concern with design production nonetheless integrates objective, measurable outcomes that are guided by – and in certain instances, may even be eligible to either support or refute – established scientific theories or systems of knowledge that describe the natural world. Certain types of architectural practices aim to be similarly guided, though even these perhaps tend less toward a focus on objective evaluation relative to established knowledge about natural systems, and rather engage more of an interest in their investigation and exploratory application. This is to reinforce the understanding that designers are at some significant risk when making claims toward contribution to the natural sciences, and that the types of constraints that guide the natural sciences regarding theoretical development and evaluation are more frequently of a fundamentally different nature than those at work in the artificial sciences. Nonetheless, Simon implies that designers should aim their experimental practices toward descriptive systems and evaluative instruments that are derived from the best possible naturally scientific understandings of both the inner and outer environments through which their designed artefacts are manifested. Careful attention to these concerns will move these practices toward a better instrumental calibration of the "thin interface" that determines the design system's capacity to make the "better" and "satisficing" choice.

The chief aim here is to begin to formulate a theory of architectural design practice that privileges a clear understanding and articulation of the discrete, experimental components that combine to formulate the material evidence of a larger experimental project. The makeup of experimental practices within both natural and artificial sciences may then be understood first according to the mixtures of their interactions to (and from) each – their practice orientation – and second according to the experimental typologies that will best support the interests of that practice, at a range of scales. Supporting experiments might then be considered for their flexibility in covering a great variety of aims for output, duration of execution, and levels of complexity in formulation and setup. This typological framework for experiment – and of locating varied intentions for experiment according to practice orientation – is meant here to provide a basis for understanding a range of experimental systems within digital-material architectural practices. These experimental systems exist at different scales within an architectural practice: some may be at a scale greater than the practice itself – such as within a "Research Programme" as described by Lakatos – while others may be much localised in scope – for example existing as a means to systematically investigate a subsystem within a larger design assembly. Yet the epistemological framework described above remains effective for engaging experimental targets at these or other scales. And within larger domains of inquiry, it becomes possible to rigorously leverage experiment as an investigative framework for novel discovery and inductively-led knowledge.

2.3 A narrative of making

Approximately three years after the founding of the Centre for Information Technology in Architecture (CITA), in a paper titled in *A Narrative of Making*

Mette Thomsen Ramsgaard and Martin Tamke formally outlined the research centre's principal method for structuring architectural design research through the production of experimental projects – what Krogh et al. characterise as a "major case" – and they claim a central role for how such projects behave as direct material evidence for the advancement of a line of inquiry. Material evidence supports the "inquiries by which the concepts, technologies and applications of the project can be tested and evaluated," and is evidenced across multiple stages of a given project's projects life-cycle, from ideation, development, deployment, through discursive reflection, and into the formulation of consequent projects and further study. The approach articulated discretises key constituent elements of individual experimental projects into three broad categories of material evidence: the *Probe*, the *Prototype*, and the *Demonstrator*. (Thomsen and Tamke 2009) These elements are formulated as interdependent representational components operating within a single experimental project (which itself in turn exists in the context of a broader theoretical framework or line of research inquiry). In this formulation, probes, prototypes and demonstrators are most normally executed (roughly in sequence) as a method for interrogating a specific set of research questions, working from ideation through the systematic generation of a 1:1 architectural construction:

1. The design probe is a design-led investigation allowing speculative inquiry, theorisation and the setting out of design criteria.

2. The material prototype is a materially-led investigation allowing exploratory testing, of craft and material behaviour. The prototype answers and develops the design criteria of the design probe.

3. The demonstrator is an application-led investigation allowing interfacing with real world problems and constraints.

Collectively, these comprise an experimental project: each element working in its own unique fashion to contribute its own essential component of material evidence to the research question at hand. Importantly, the focus of interest that each of these individual elements constitutes is ultimately continuously extended through the research practice as a whole: there is no "final" result to any project, but rather a collection of open-ended offerings, including the theoretical support or refutation of a series of hypotheses; contributions to state-of-the-art tools and instrumental methodologies; and the pointing toward new questions or lines of inquiry.

This methodological framework for CITA as a larger research practice provides

Figure 2: Design probe exploring growth through goal-seeking stochastic fractal trees.

the primary foundation for this research project specifically, with these definitions of material evidence creating both a primary theoretical platform for research interests, as well as an operational diagram for its experimental pursuits. This base framework has been adopted, but also expanded upon to support the argumentation of this thesis and as part of its theory of practice.

2.3.1 Experimental projects and supporting experiments

For this research project, the term "experiment" addresses investigative frameworks that comprise multiple and varied scopes of interest, explanatory ambitions, and instrumental purposes. Experimental projects as described above may then be understood as collections of a broader set of underlying systems, each of which has its own purpose. Yet many of the underlying systems that drive them – especially at the level of the probe and prototype – constitute their own investigative frameworks, and in certain capacities fulfil the criteria for being considered experiments in their own right. Even as these underlying systems advance the larger "major case" projects they participate in, these experiments frequently have epistemological lives of their own – for example, contributing to local instrumental purpose, as Allan Franklin suggests in performing "checks and calibration" or participating in the "manipulation" of a modelling or experimental apparatus, or simply as investigative or exploratory tools. Systems in this second mode are here considered supporting experiments.

Figure 3: Design probe exploring soft body simulation of colliding multiple inflated elements.

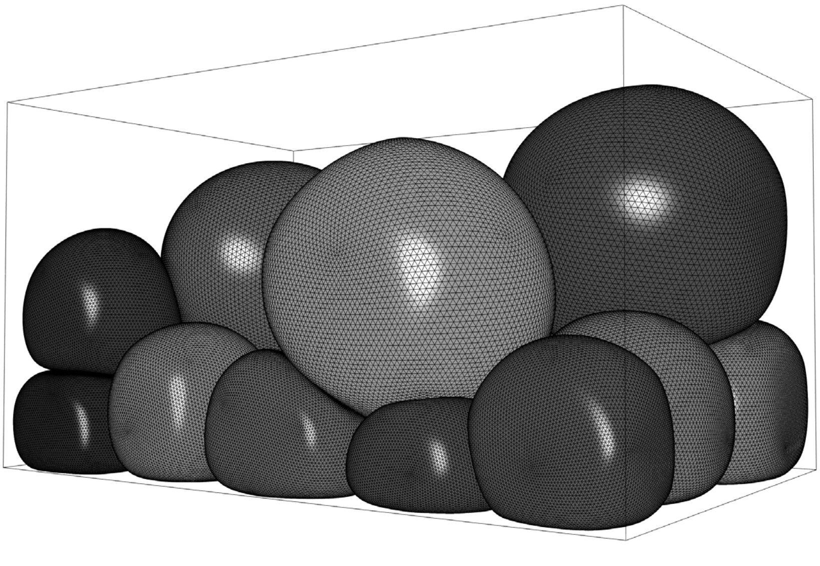
Supporting experiments by nature have more locally defined ambitions, most typically helping to formulate the individual elements that comprise the experimental project and elicit its performance as a holistic entity. While experimental projects tend to follow a better-established and well-defined overall organisation, supporting experiments are much more diverse in their makeup. In conjunction with one another, these modes implement the primary action-based research ambitions and operations of the research project. And while supporting experiments principally exist as discrete components within experimental projects, "one-offs" are occasionally engaged, such as for:

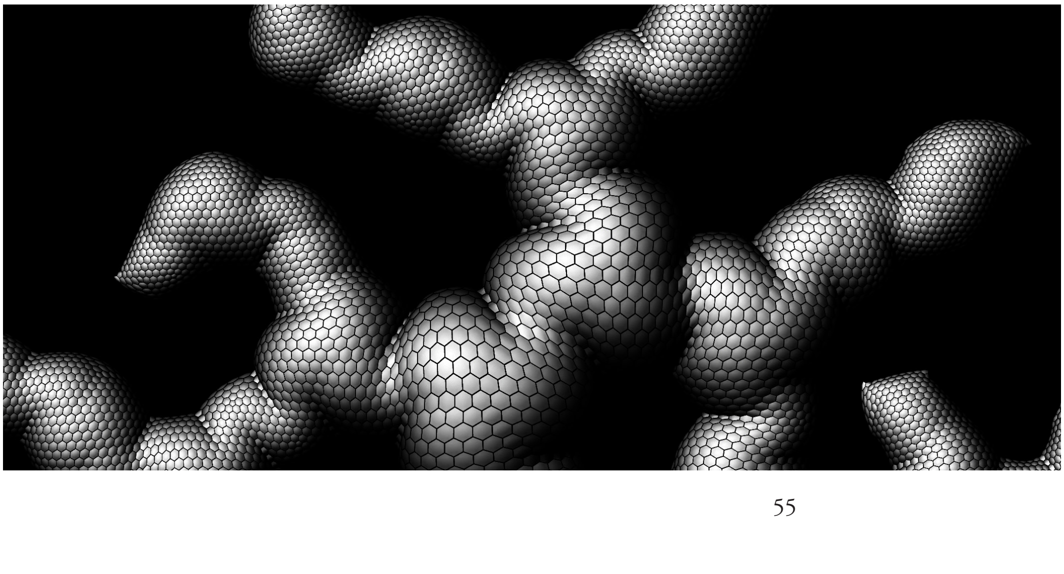
Figure 4: Design probe exploring branching growth topologies and morphology derived from inflation

1. the development of general tools that are believed to have independent value or anticipate future use elsewhere.

2. as means to investigate ideas of interest that are either situated between multiple experimental projects.

3. as stand-alone micro-investigations that may suggest or dismiss





further inquiry.

In this context, this research project then considers especially the design probe as a form of material evidence that merits further unpacking. While the design probe operates chiefly as a flexible space for the initial material explorations of an idea, its specific consideration as a mode to produce or be effected as a design instrument merits epistemological separation. This separation of investigative probe from design instrument is not rigid. In fact, design instruments may emerge partly or even wholly absent of intention when a probe is initiated. What is most productive in separating instruments as their own type of probe is in clarifying their potentials to work across multiple experimental projects, and to work as effective means to bind larger projects along shared topics of interest. This supports both clearer theoretical inquiries or pursuits across a wider scale and results in the better articulation of eventual model setups.

For this research project then, design probes have in many cases operated purely as singular modes of inquiry, operating as one-off interpretations, syntheses or speculations based on research processes either invented internally or interpreted from descriptions afforded by other practitioners within related fields of study. But, they have generally operated as initialising design explorations, sometimes meriting further development into more generalised design or theoretical, platforms or ultimately evolving into operators for full-blown experiments.

2.3.2 Experimental project setup

These key modes of material evidence – investigative probes, instruments,

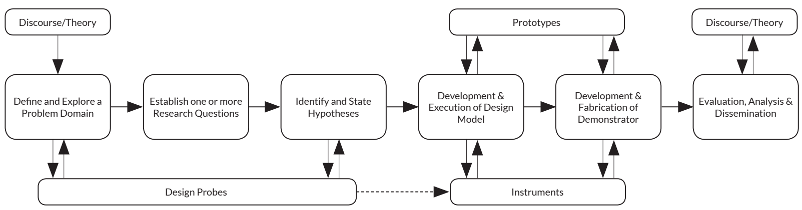


Figure 5: Basic diagram for experimental project setup in this research project

prototypes and demonstrators – ultimately support a narrative of making, where ongoing investigations across multiple experimental projects encourage continuous support for testing existing hypotheses while simultaneously encouraging the formulation or adoption of new vehicles of inquiry. For this research project, material evidence has been chiefly produced within a general methodology for setting up and executing individual experimental projects that largely maps to setups commonly associated with the scientific method.

Each experimental project generally follows a shared sequence:

1. **The identification of one or more topics of interest, or problem domains**: a problem domain presents a useful vehicle of inquiry for an experimental project. Problem domains emerge from a variety of sources, including concerns identified in existing theoretical discourse, based on empirical observations within practice, or attending a specific, externally provided design brief. It also bears a relationship to some initial investigations that seek to more clearly define its boundaries or explore its potentials. Collaborative or highly complex projects will often be expected to support multiple problem domains (indeed, this support of multiple research ambitions is itself a recurring problem domain that may be actively sought).

2. **The establishment of one or more research questions**: Research questions articulate directions of inquiry into the defined problem domain. For any given Experimental Project, multiple questions will often but not necessarily be closely inter-connected with one another.

3. **The establishment of one or more hypotheses**: In general, a hypothesis for an Experimental Project makes proposals that directly address one or more research questions. Experimental design posits that the application of the defined design approach will either result in or be required of either a specific type of process or outcome.

4. **The development and execution of a digital design model network, and attendant physical prototypes**: This operates as a primary testing vehicle for the hypotheses, working to manifest their proposals, and ultimately to evaluate them. It embodies a great deal of investigation, digital tooling, design work, assembly detailing, and direct engagement with the target material systems and assemblies to be used for the demonstrator.

5. **The manufacturing and assembly of an architectural demonstrator**: The physical establishment of an architectural assembly becomes a critical object in the evaluation of hypotheses, provides a basis for critical reflection of the design system, and operates as a primary mode of dissemination.

6. **Analysis, contextualisation and dissemination of the process and results**: Experimental Projects are ultimately made relevant through analyses of their outcomes, specifically as they reframe and

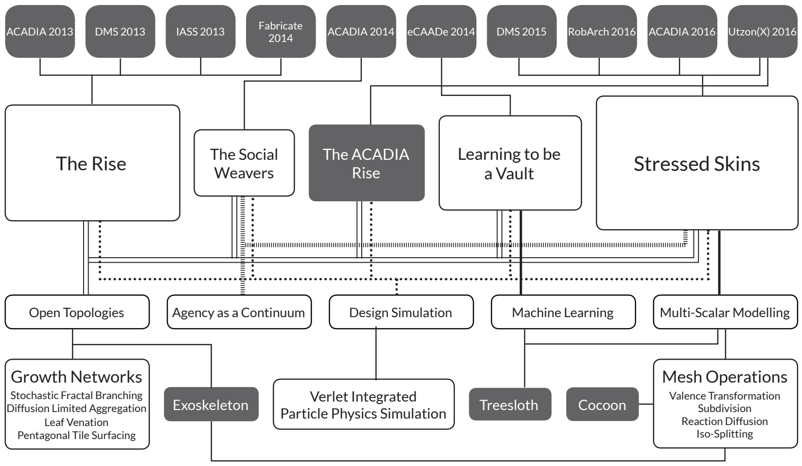
contribute back to those components of discourse relevant to the problem space defined.

This basic framework for the execution of experimental projects suggests that the chief interfaces afforded through this setup exist at both initiation and conclusion of a project. While the principal contribution to discourse is typically made upon the completion of a given experimental project, the deliberate formulation of investigative probes and instrumentation as semi-independent supporting experiments entities enables them to interact not only within a single project, but also across multiple experimental projects.

2.3.3 Experimental ecologies

This chapter has argued for an understanding of experiment – within both the

Figure 6: (From top to bottom) Publications, experimental projects, vehicles of inquiry and supporting experiments for the research project.



natural and design sciences – that is broadly heterogeneous, variably engaged in knowledge production along an axis of reasoning that ranges from the inductive to the deductive. Experiments have also been framed according to their scale within a narrative of making because much of the action pursued through this research project focused on its production of experimental content at the scales of both embodied material evidence and the larger experimental projects to which these contributed. As these different elements are synthesised, an ecological understanding of a research project emerges, where the interdependence between constituent elements elicits or suggests holistic characteristics.

Figure 6 provides a topological mapping of the principal elements that constitute this research project, illustrating how they are situated relative to one another and within in the overall project ecology. They are generally presented in chronological order of emergence within the design project (within the diagram from left to right) and are broken out into four broad component types (within the diagram from top to bottom):

1. **Publications** have provided formal means to disseminate findings for this research project. The diagram illustrates the peer-reviewed publications for which I am listed as an author, and the conference proceedings or books to which these works have contributed.

2. **Experimental projects** have been defined as comprising the principal substance of this research project. I have been a principal investigator on five experimental projects in this research project: a) *The Rise*, b) *The Social Weavers*, c) *The ACADIA Rise*, d) *Learning to be a Vault*, and e) *Stressed Skins*. The diagram presents each of these projects with its size relative to its overall contribution to the research project in total. Both *The Rise* and *Stressed Skins* may therefore be characterised as major projects, while *The Social Weavers*, *The ACADIA Rise*, and *Learning to be a Vault* may be characterised as minor, or sketch projects.

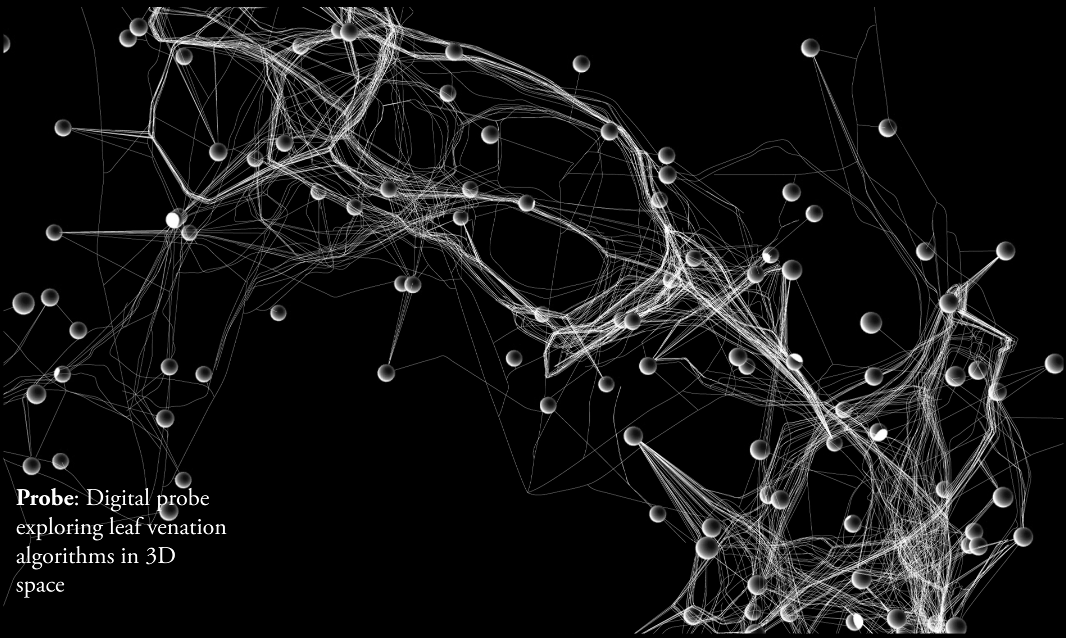
3. **Vehicles of inquiry** form investigative frameworks which embody problem domains that are both targets of epistemological interest and may be activated directly within design modelling practices. They help elicit research questions, inform hypotheses, and suggest arguments at the point of discursive interface for research projects. The chief vehicles of inquiry pursued within this research project include: a) open topologies, b) design simulation, c) agency as a continuum, d) machine learning, and e) multi-scalar modelling.

4. **Supporting experiments** have been previously defined as either probes or instruments. Respectively, these have been used to initiate or pursue investigations, or to instrumentalise operations. Instruments work either as component parts within a larger experimental project, or as stand-alone systems.

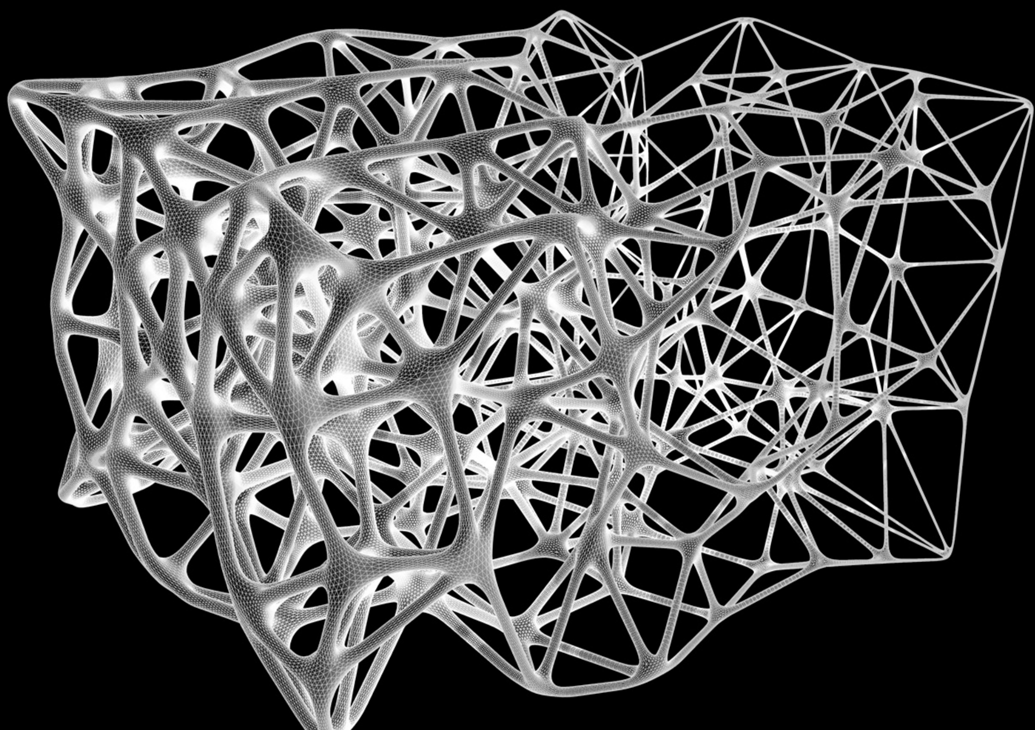
2.4 Methodology

This dissertation is being submitted to achieve a PhD by publication. The substance of its findings has principally produced through a process of research through design that delivered five experimental projects, each of which has been attended by the dissemination of its findings in exhibitions, peer-reviewed conference proceedings or book chapters, and through the publication of free digital modelling tools to the design community. This section will define

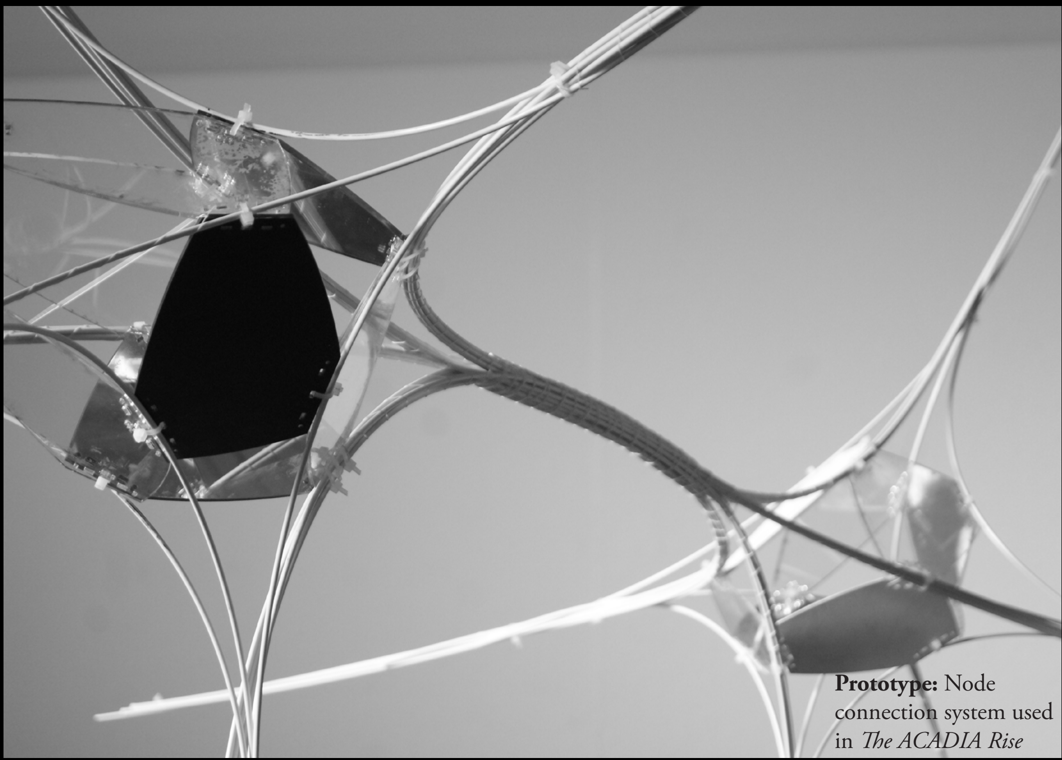
Experimental Ecology for *The ACADIA Rise*



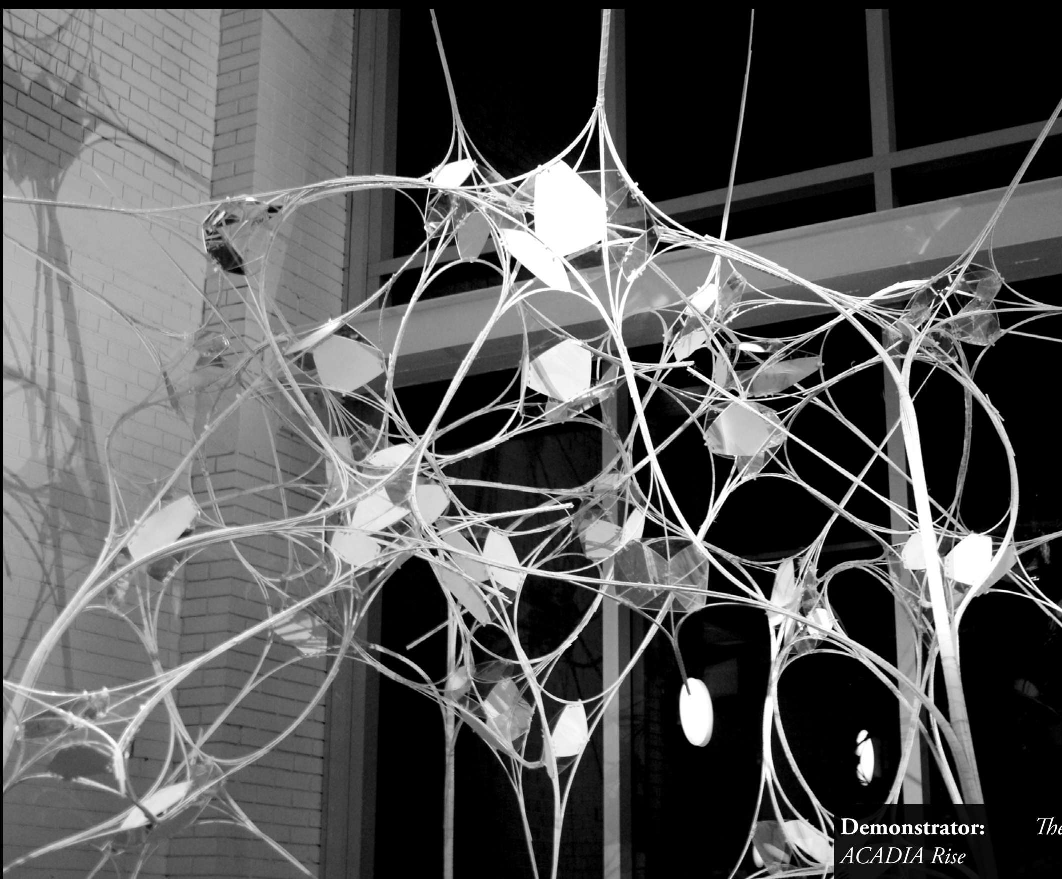
Probe: Digital probe exploring leaf venation algorithms in 3D space



Instrument: Example of Exoskeleton plug-in output



Prototype: Node connection system used in *The ACADIA Rise*



Demonstrator: *The ACADIA Rise*

these contributions within the contexts established previously in this chapter, framed through the four component types previously described, and especially considering the ecological nature of their formulation in how they relate to one another within and across scales, ranging from model element to practice.

It will first identify the primary vehicles of inquiry that have motivated and connected experimental content and provided important points of departure for identifying and mapping new information spaces. I will finally introduce the specific publications whose findings are presented as evidence of knowledge contribution, and how they work in concert to support the primary arguments of this research project, which defines an instrumental framework and theory of practice that supports the application of adaptive parameterisation in practice.

Here, adaptive parameterisation describes a methodology for model formulation in computer-aided design for architecture and the building sciences. It privileges and is oriented toward the development of computational models – those which engage in algorithmic modelling practices – based on the potentials these confer for increasing design intelligence. It is predicated on the observation that contemporary architectural projects are designed, developed and delivered through a network of multiple, discrete, variably-purposed modelling systems. In this context, it identifies the input and output parameters – or feature spaces – that principally constitute the thresholds between discrete computational models as targets of especial epistemological interest. Adaptive parameterization then focuses on the development and deployment of data structures for these feature spaces – that exist between models – that are capable of operating across multiple model scales and intentions: these data structures work as mutable substrates for managing and conveying design intelligence created through the dynamic activation of algorithmically-driven, computational modelling systems. Such data structures become capable of enabling, supporting, and enhancing bi-directional constraints between multiple, discrete modelling systems, eliciting increasingly holistic performances from the various, discrete models that are necessarily bound together in the realisation of architectural projects.

2.4.1 Experimental projects and related publications

Each of these vehicles of have been pursued within various experimental projects and supporting experiments. This section briefly introduces each of the five experimental projects that have used these vehicles of inquiry in their formulation, development, and discursive interface, and for which I have performed as a principal investigator. Additionally, a list of publications that have disseminated findings for each project – and for which I am a contributing author – has been included at the end of its description. These publications have been noted when they are not being submitted as part of this dissertation; the reasons for their lack of inclusion are chiefly because their content as it relates to this research project specifically may be redundant to other publications being submitted, or my role as an author was limited to a supporting role. Each publication will be presented as part of this dissertation, and there will be preceded by a short summary that more specifically describes my own role as an author, how my contribution to the text relates to my overall contribution to the experimental project. Each summary will also provide in more detail how the paper relates to the overall hypotheses presented in this research project.

Each of these projects has been pursued as a collaborative effort, chiefly with other members of CITA who have also participated in the Complex Modelling project. Collaboration has been a central feature of this PhD project. In each of these projects my role – in addition to informing research interests and discursive engagement – has been as lead model developer. The interrogation of the modelling environment, and efforts to pursue each vehicle of inquiry for its instrumental capabilities within applied experiments has been central to the production of knowledge embedded within this project. The experimental projects are here presented in chronological order of their development. Each project also maps to or informs one or more of the peer-reviewed publications that have been submitted as part of this dissertation.

The Rise (2012-2013)

The central conceptual driver of *The Rise* is the idea of a growing architecture: it was designed for "ALIVE – Designing with Living Systems", an exhibition curated by Carole Collett and held at the Fondation EDF in Paris in 2013. The installation has its own internal growth patterns that both guide and are guided by its composite material in a highly distributed aggregation of small members that branch, multiply, and attach back both to each other and their environment. The installation examines distributed systems as an alternative to traditional structural systems. In this alternative vision, architecture is not a static formalist proposition but is instead seen as continuously adapting to the dynamics of its surroundings while growing into form.

This model diagrammatically emulates natural plant growth processes whose properties are called tropisms. These include such environmentally triggered

Figure 7: The demonstrator for *The Rise* at the Fondation EDF in Paris. Photo by Anders Ingvartsen

mechanisms as those reacting to light (phototropism), gravity (geotropism) or touch (thigmotropism). In plants, these stimuli trigger auxin, a hormone that directs new cellular growth and coordinates the emergence of the plant's shape. For *The Rise* virtual auxin is activated in response to the exhibition space through programmed algorithmic tropisms. The installation then grows in response to its environment, extending and directing its morphogenesis according to the variations of light in the space, gravity and its contact to the surroundings, all enacted through the affordances and limitations endemic to its own materiality. Like plants the system is self-aware. It understands its behaviour under self-weight and reacts through thickening or weakening or shoots that create extra support. The installation learns from nature and mimics its ways of creating structural performance, but also expands this into new hybrid growths that are more rarely found in the natural environment, such as in the branches' ability to re-join and create circular relationships with high structural strength.

The growth takes first place in the digital design space, where a growth algorithm is applied within a context of ongoing simulation, calibrated to the behaviour of the material, growth towards the direction of sunlight. With constant feedback from the environment and its intrinsic tension and compression forces, the computational model iterates through several states set up by the designer, and acquires a final state that is directing the production.

The Rise has been featured in the following publications:

- Tamke, M., Stasiuk, D. & Thomsen, M. R. "The Rise: Material behaviour in generative design." In: Proceedings for ACADIA 2013: Adaptive Architecture. (Association for Computer Aided Design in Architecture). [Not submitted as part of this dissertation]

- Tamke, M., Stasiuk, D. & Thomsen, M. R. "ALIVE: Designing with aggregate behaviour in self-aware systems." In: Proceedings for the Design Modelling Symposium Berlin 2013: Rethinking Prototyping. (Design Modelling Symposium).

- Tamke, M., Evers, H. L. & Stasiuk, D. "Growing Timber Structures: Growth algorithms as an alternative approach for integrating design with constraints from materiality, tectonics and production." In: Proceedings for the International Association for Shell and Spatial Structures 2013: Beyond the Limits of Man. (International Association for Shell and Spatial Structures).

- Tamke, M., Stasiuk, D. & Thomsen, M. R. "The Rise: Building with fibrous systems." In: FABRICATE 2014: Negotiating Design & Making. (FABRICATE). [Not submitted as part of this dissertation]

The Social Weavers (2013)

The Social Weavers is a bending active, non-standard grid shell structure made from fibre composite rods of variable diameter and stiffness. The installation develops aggregate self-forming processes that intersect with the behavioural activation and distribution of fibre-composites under design direction to produce a novel architecture. *The Social Weavers* installation is conceptualised as a nest. It is comprised of multiple, actively-bent splines that are articulated through a network of collected, interwoven elements, whose local behaviours aggregate into a globally non-linear structural assembly. The central component of the design model for *The Social Weavers* is the custom-written, Verlet-integrated particle simulation library that is set up specifically to allow for collections of particles to be organized through unfixed and transitional topologies. It allows for the incremental addition of new elements over time,

Figure 8: *The Social Weavers*. Photo by Peter Bennets

and for existing elements to continuously undergo reassessment of the force relationships in which they participate.

The Social Weavers' modelling systems investigate the development of complex, open-ended design spaces, with an especial focus on the implications of agency in the formulation computational design models. It considers an understanding of design agency that identifies bottom-up processes as distinct from top-down approaches. In this context, it examines how open-ended design modelling systems that implement tight, simulation-based feedback loops for the integration of material behaviours may limit designer agency: as morphogenesis increasingly relies on algorithmic bottom-up systems to produce an artefact, the designer's top-down authorship becomes increasingly relegated to boundary definition and initial parameterisation. *The Social Weavers* becomes a means to question this dichotomy and identify an alternative approach that considers agency along a continuum, where both designer authorship and algorithmic systems that take advantage of the flexibility of open topologies may be better synthesised.

The Social Weavers has been featured in the following publication:

- Nicholas, P., Stasiuk, D. & Schork, T. "The Social Weavers: Negotiating a continuum of agency." In: Proceedings for ACADIA 2014: Design Agency. (Association for Computer Aided Design in Architecture).

The ACADIA Rise (2013)

CITA was invited to the ACADIA 2013 Conference in Cambridge Ontario to hold a design/build workshop. The workshop took its point of departure from CITA's earlier project *The Rise* and further developed this research in the digital design and fabrication of aggregations of variably sized bundles of fibre material that multiply, bend, branch, and recombine in a distributed assembly that manifests an alternative to traditional structural systems, further exploring the conceptualization, technologies and making of an architecture that is continuously sensing and dynamically adapting to its environment as it grows into form. The workshop participants received insights into the algorithmic basis for the digital model, and both the CNC and physical processes of fabrication in a hands-on way.

For this phase of research, the focus was on exploring specifically adaptive systems. Here, adaptive systems are understood not only as geometrically variable assemblies, but more importantly as topologically dynamic entities capable of organizational variation in response to locally differentiated performance requirements. To achieve this capacity for dynamically adaptive open topologies, *The ACADIA Rise* specifically examines recombinative structural branching. Here, convex polyhedra are deployed as compression shells to structurally fix nodes of branching elements. The number, orientation, and performative functions of the elements in each polyhedron are determined entirely as an adaptive response to local structural needs and the installation's desire to continue its growth. The final assembly operates as a synthesis of hard and soft members, of actively-bent elements knitted together into a strong,

Figure 9: Detail from *The ACADIA Rise*

truss-like configuration.

The ACADIA Rise has been featured in the following publication:

- Stasiuk, D. & Thomsen, M. R. "Digital Simulation for Design Computation in Architecture." In: Bricks | Systems 2016. Aalborg University Press.

Learning to be a Vault (2014)

Where parametric modelling allows designers to work in flexible ways with variable geometries, the associated problems of parameterisation and reduction are well known. Parametric models are normally limited because they necessitate a pre-configuration of their embedded variables as well as a pre-determination of model topology, meaning that the designer needs to know all defining parameters and relationships between model elements at the start of the design project. *Learning to be a Vault* operates as an experiment that tests new methodologies for the modelling of design systems that challenge this standard of configurational fixity by opening parameter spaces in both variable value and element connectivity, while simultaneously embedding material

Figure 10: Selected detail models for *Learning to be a Vault.* Photo by Anders Ingvartsen

behaviour within morphogenesis. The aim for the project is to establish methods for designing with open topologies in which the dependencies between parameters are emergent and open to change during the design process. To this end, multiple learning strategies – including evolutionary and unsupervised classification algorithms – are deployed in the interrogation of a broad design space.

The project takes point of departure in a series of physical models developed in a workshop held at IAAC in Barcelona with the Digital Matter // Intelligent Constructions 2013-2014 Master's studio led by Areti Markopoulou, with Alexandre Dubor and Moritz Begle. These were used in the development and examination of a simple system of actively bent arches that become networked together in the formation of novel vaulted configurations. These models are made of rattan, a tropical climbing plant most generally used in wicker furniture and basket-making. Rattan is light, flexible, and effective for rapid explorations of active-bending material systems. Through the exploration of these networks as morphogenetic rule-driven systems for incremental formation, the students were charged with creating a related series of variables available for deployment in a multi-objective evolutionary model. The set of simple goals that emerged from this process of rapid physical prototyping are related to material usage, the generation of variable spatial configurations and structural performance and capacities. A digital model was then developed based on sets of simple rules for both the generation and the performance-based analysis of each model instance – or phenotype. This modelling process relies on a spring-based simulation system for the instantiation of embedded material behaviours [Kangaroo] and processing through a multi-objective evolutionary algorithm [Octopus] for performance assessment across the established optimisation parameters.

The deliberately open-ended design system established allows for a range of phenotypes to emerge and be quickly analysed for performance quality according to the established optimisation goals. This multi-objective evolutionary approach intentionally produces a high volume of phenotypes, which can become extremely varied and intractably numerous for gaining an understanding of any chief typologies that may emerge from using such a process. Yet it is exactly in this variety that valuable opportunity for design exploration is embedded, and through the classification processes enabled through unsupervised learning, the designer is empowered to gain a richer understanding of the design space.

The experimental methodology lies in the examination of the design space through the processing of the resulting taxonomy of evolved model results through learning systems of classification. Here a K-means algorithm was implemented on a collection of 18 variables that may individually be understood as banal numerical descriptions of each model's geometry, but which when processed through the algorithm allow for a deeper intuitive understanding of overall formal tendencies between the evolved outputs. Because the results of the evolutionary solver have been optimised according to numerically expressed performance measures, it becomes interesting to think of classification such that the existing input variables will not provide immediately obvious means for segmenting or understanding desirable outcomes, and that alternative means of analysis instead become necessary for a more robust understanding of the results. Novel typologies not only emerge through such a process, but more importantly the designer is given new means to both understand and explore the broad design spaces that result from the deliberate application of open-ended design systems.

Learning to be a Vault has been featured in the following publication:

- Stasiuk, D. & Thomsen, M. R. "Learning to be a Vault: Implementing machine learning for design exploration in inter-scalar systems." In: Proceedings for eCAADe 2014 Fusion: Data integration at its best. (Education and research in Computer Aided Architectural Design in Europe).

Figure 11: *Stressed Skins* demonstrator at the Danish Design Museum

Stressed Skins (2014-2015)

Stressed Skins was an installation designed and fabricated by the Centre for Information Technology and Architecture (CITA) as part of its ongoing Complex Modelling project. The installation design and fabrication processes were motivated by several vehicles of inquiry. In addition to the continued exploration of open topologies and design simulation, here the primary vehicle of inquiry was the investigation of multi-scalar modelling techniques, with an aim to better understand their potentials within the discipline of architectural design modelling for generative, analytical, and fabrication-related processes. The potentials of a multi-scalar modelling approach explored here apply to the computation of specific material properties in the context of experimental structural systems and digitally-driven production processes. Fundamental to these interests was the development and implementation of a method for managing data structures within and across the multiple models required for each stage of the supply-chain, from concept to build.

The material and assembly system used was of incrementally-formed, thin-sheet steel panels arrayed within a stressed-skin structure. The technique used was robotic single-point incremental forming (SPIF), whereby the slow application of a point force along a proscribed toolpath to a thin steel sheet steadily pressed it into bespoke forms. The effects of this process are both geometric, and materially transformative. The geometric effects allow for the steel sheets to be pressed such that, when set against an opposite panel, they can produce both structural depth and connection. This integration of structural depth directly within the panels allowed for the construction to experimentally investigate the possibility of a frameless stressed skin. The effects of the material transformation are such that strain hardening is locally introduced into the material to different degrees, depending on the depth and angle attained through the SPIF process. These variable material effects and properties were central to the multi-scalar modelling interests, which sought to understand the structure at several scales from the macro to the meso to the micro.

Stressed Skins has been developed with the understanding that the application of a single-model approach for the managing all the design interests and processes for projects of even modest complexity is at least inflexible, and more frequently intractable. An experimental aim is to explicitly describe a methodology that alternatively privileges the development of a model network of heterogenous sub-elements that are calibrated to work both independently and in conjunction with each other, with minimal loss of information between. The modelling process for the project then focuses on engaging in adaptive parameterisation, identifying and deploying an interface that can negotiate changes in model scale while retaining critical information about geometry and material properties. Here a half-edge mesh data structure was investigated for its suitability to operate as the primary vehicle for geometry development and model traversal. Half-edge mesh data structures allow for the efficient topological reading and transformation of mesh objects. Meshes of many types are routinely used for managing data structures related to both simulation and analysis within structural assemblies, but half-edge meshes are particularly well-suited to support the remeshing processes that are central to a multi-scalar modelling approach. Indeed, careful management of such a data structure allows a designer to effectively couple it with key information that persists across these different scales throughout the different stages of the design process.

Central to the network model ecology was the development of both new implementations of existing computational approaches, and the formulation of novel techniques and tools for form finding. These all took advantage of different capabilities of half-edge meshes, and in particular their utility in coupling geometry with multiple layers of semantically rich data about the assembly system. Through the development of these instruments, the model network became capable of producing coincident understandings of coarser topological relationships between individual panels in relation to each other within and across skins, granular understandings of local material behaviours related to geometric transformation within each panel, and highly refined geometries for defining digital fabrication drivers and toolpaths.

Stressed Skins has been featured in the following publications:

- Nicholas, P., Stasiuk, D., Noørgaard, E., Hutchinson, C. & Thomsen, M. R. "A Multiscale Adaptive Mesh Refinement Approach to Architectured Steel Specification in the Design of a Frameless Stressed Skin Structure." In: Proceedings for the Design Modelling Symposium 2015: Modelling Behaviour. (Design Modelling Symposium).

- Stasiuk, D. & Thomsen, M. R. "Digital Simulation for Design Computation in Architecture." In: Bricks | Systems 2016. Aalborg University Press.

- Nicholas, P., Stasiuk, D., Noørgaard, E., Hutchinson, C. & Thomsen, M. R. "An Integrated Modelling and Toolpathing Approach for a Frameless Stressed Skin Structure, fabricated using Robotic Incremental Sheet Forming." In: Robots in Architecture 2016. (Association for Robots in Architecture).

- Nicholas, P., Zwierzycki, M., Stasiuk, D., Noørgaard, E. & Thomsen, M. R. "Concepts and Methodologies for Multiscale Modeling: A Mesh-Based Approach for Bi-Directional Information Flows." In: Proceedings for ACADIA 2016: Posthuman Frontiers. (Association for Computer Aided Design in Architecture). [Not submitted as part of this dissertation]

- Nicholas, P., Zwierzycki, M., Stasiuk, D., Nørgaard, E., Leinweber, S., & Thomsen, M. (2016). Adaptive Meshing for Bi-directional Information Flows. In Advances in Architectural Geometry 2016. vdf Hochschulverlag AG Zurich. (Advances in Architectural Geometry). [Not submitted as part of this dissertation]

- Nicholas, Paul, Mateusz Zwierzycki, Esben Clausen Nørgaard, Scott Leinweber, David Stasiuk, Mette Ramsgaard Thomsen, and Christopher Hutchinson. "Adaptive robotic fabrication for conditions of material inconsistency: increasing the geometric accuracy of incrementally formed metal panels." Fabricate 2017 (2017): 114-121. [Not submitted as part of this dissertation]

2.5 Conclusion

This chapter has presented a theory of practice that engages in action-oriented – or constructive design – research – based on Stan Allen's description of a material practice. This theory of practice has been presented as the central methodology employed for this research project and dissertation. Its approach is defined by the circular or catalytic relationships that it affords between design production and theoretical discourse. It has outlined that such an approach supports the explicit treatment of computer-aided design systems as targets of epistemological interest, beyond their role purely as supportive technological devices, and defined this framework as a digital-material practice.

In either a research or professional context, the digital-material practice pursues the cyclical production of both design artefacts and discursive contribution through experiment. This chapter has examined the epistemology of experiment, specifically in how it relates to design practices. It has done so through an examination of the distinguishing features of experiment for both the natural sciences and design practices, or, as Herbert Simon frames them in this context, the artificial sciences. In this examination, it has identified two principal axes along which experiments may be evaluated. The first of these applies to the types of reasoning that may be employed in the formulation and implementation of the experiment: whether it is more deductive or more inductive. Deductive approaches tend toward formulating experiment as a means to test existing theory, in contrast with inductive approaches which tend toward using experiment as a more investigative or exploratory device. The second axis describes the intentionality of the experiment: whether it is intended to provide or support an explanatory framework or to introduce or identify a goal-seeking intervention. The natural sciences tend to be more interested in creating explanatory frameworks, whereas the artificial sciences tend to be more interested in designing interventions into the status-quo to enact different, desirable conditions. By understanding how any given experiment exists relative to these spectra, the digital-material practitioner more precisely locates the intentionality and epistemological makeup of a given experiment. This is especially important for understanding not only how each experiment may interface with theory or discourse, but also how many, inter-related experiments may work in conjunction with one another. Along these lines, this chapter has presented this research project according to understanding its experimental collections as fundamentally ecological in nature.

This chapter has also introduced the principal body of this research project through brief descriptions of the primary, larger-scale experiments that have been undertaken, touching on both the instrumental or material modelling systems implemented for each as well as the principal vehicles or inquiry or targets of theoretical or epistemological interest engaged in with each. This following chapter seeks to further unpack the theoretical frameworks that have motivated this research project.

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3. State of the art: Model Networks

Contemporary architectural projects are almost ubiquitously undertaken through the employment of multiple, discrete digital models, each of which may support one or more roles along the design and project development chain, such as for: concept exploration or initial design; analysis, iteration or detail development; manufacture, fabrication or installation. Because the functional output for each of these models varies and their roles as representational engines are limited to the description of a subset of the overall design, these should be understood as partial models. For a more complete understanding of a project's design and development trajectory – its inception, growth and development across its life-cycle from ideation to construction and occupancy – it then becomes necessary to read, interpret, or engage these underlying partial models according to the dependencies that tie them together: to engage them as constituent to a broader model network. Models networks are a topic of interest here and evaluated partly by the richness and depth of the representations they must generate, command and control, and partly by the quality and nature of the feature spaces that act as the information thresholds between each discrete, functionally specific partial model.

Model ecologies

Any given model network may be regarded as essentially ecological in nature, and therefore exhibiting holistic behaviours. While the term *ecology* is originally biological in nature, it also supports extension into systems in non-biological fields, where any ecological system may be recognised such that the processes, outputs or outcomes for each of its constituent elements are important not only for their own phenomenological manifestation, but also especially for the relationships, dependencies, and feedback loops that exist between them. These exchanges between discrete elements become inextricably tied to the system of interest's global or unified whole. The combined effects for each element's actions along with dependent or feedback-driven consequences for other elements within the ecology then describes the *holistic* behaviour of the design modelling system.

Considering that model networks reflect ecologies with holistic performance characteristics, it follows that the health of these ecologies then becomes a topic of critical importance, leading us to pursue methodologies that support an increasing diversity of models being effectively organised in relation to one another in order to contribute to more efficacious resolutions across intended functions. Model health describes both functional efficacy, flexibility, and robustness. A healthy model network should not just support open-ended modelling methods for architectural designers as they investigate and resolve the variety of constraints present in a design brief, but also help identify and address those emergent constraints that are inevitably revealed through the iterative design processes and which attend the development of complex architectural projects. Crucially, it should allow for findings or intelligence gains found at different stages in the modelling process to effectively feed forward (or back) into other interdependent modelling processes. It is therefore important to define and develop design modelling methods that explicitly target the formulation of partial models according to how they can more effectively relate to one another in eliciting desirable, holistic performances. While there may be many ways to achieve this performative behaviour, this thesis presents *adaptive parameterisation* as a modelling methodology that is well-suited to elicit such desired holistic performances from complex model networks.

Adaptive parameterisation

Adaptive parameterisation has been introduced as a method for developing modelling frameworks that focuses on the information thresholds that exist between discrete partial models and considers how their effective formulation elicits the production of new design intelligence holistically across the modelling system. Adaptive parameterisation refers to modelling setups that facilitate the *dynamic activation* of *mutable substrates*. Here a mutable substrate is comprised of a topologically open-ended but organisationally persistent data structure that (at least partly) defines the parameter spaces which operate as thresholds between different partial models within the network. These data structures behave as synthetic information carriers whose geometric elements may be directly imbued with locally differentiated, semantically rich, descriptive labels. This flexible parameter space is thus configured to support the dynamic activation increased design intelligence through a series of algorithmic methods that accumulate, transform, integrate, and command its underlying elements across the range of the project's demands for design and realisation. Crucially, this dynamic activation creates bi- or multi-directional constraints between discrete modelling systems, embedding interdependent relationships between models through more robust feedback loops, and enhancing the modelling system's performance.

It is important that these data structures and algorithms are configured to support the frequently heterogeneous makeup of the underlying partial models operating within complex networks, which are varied at least according to both typology and intent. For example, while certain partial models may be responsible for leveraging bottom-up, algorithmically driven agents to enact complex algorithmic transformations, others may necessarily be deployed through more explicitly directed, top-down interventions from the designer, such as in the definition of site constraints. Model setups that effect positive holistic performances from their composite partial models negotiate this heterogeneity through the establishment of flexible data structures that ensure that the information produced along each stage of the supply chain will effectively interface with others, ensuring that wide ranges of design concerns can not only be reconciled, but used to enhance the performance of each other. This may be effectively achieved though the support of more robust feedback loops or the establishment of bi- or multi-directional dependencies between partial models.

3.1 Representational engines

Architects work chiefly through the production of representations, through which information about the designed artefact is communicated. These are varied in both their *media* and *intention*:

"Architecture is already implicated in a number of media, and the architect is out of necessity constantly moving from one medium to another, transcoding from virtual to actual and vice versa. To move from drawing or writing to building (and back again) is only one example of this; architecture's constant transactions with and actualizations of social, technical and urbanistic variables are perhaps more significant. Historically, architecture has deployed a limited catalogue of techniques to negotiate the actual and virtual: techniques of projection, calculation, or notation, for example. In recent practice, this catalogue has been incrementally expanded...by the simulation and visualization capacities of the computer." (Allen, 1998)

The practice of architecture has then demanded of designers an ability to negotiate this great variety, and crucially, to sequence or synthesise multiple representations for both the generation and description of design ideas. A few examples of intention for these representations may include: the expression of abstract, idea-oriented or fantastical imaginings; the communication of design motivations, potentials, or constraints; the development or implementation of functionally generative tools for design exploration; the collation of analytical results or process descriptions; the production of outputs for communicating schematic organisation, documenting construction, or supplying direct drivers for fabrication and construction. Media may include: physical models, digital models, diagrams, collage, renderings, schematic drawings, prototypes, shop tickets, schedules, descriptive text, or alphanumeric data sequences for toolpath assignment for computer-controlled devices.

Of course, neither list here reflects any new knowledge nor is by any means exhaustive, with each only beginning to enumerate the great diversity of potential embedded in both the goals and mode of delivery for any given architectural representation. The aim here in introducing architectural representations thus is not intended to identify the study of architectural representation as an object of epistemological focus for this research project, but rather to support the basis for a key assumption for this research: that the development and delivery of architectural projects of even the smallest scale results in and requires the production and management of an ecology of multiple, inter-related representations in support of ideation, design, development and execution. This research project identifies the variegation implicit in this production as a particularly interesting opportunity for leveraging good design practice, and it is an aim for this research to unpack some simple observations regarding the natures of and potentials embedded within this variegation in intention and media. Importantly, these diversities of both intention and type for representation correspond to the variety not only in the roles that architects (or other stakeholders) must perform at different points during a given project's life cycle, but also to the range of potential approaches available to them to execute a given task.

Of the different media instruments available to designers, over the past quarter century digital modelling systems have emerged as the primary production platforms through which projects tasks are formulated and managed. In this context, the intention for many – if not all – partial models is to support an extraction of specific key information about the designed artefact: in effect, to operate as a representational engine that either helps to generate or inform one or more other representational engines in a model network.

The functional interplay of multiple partial representations features as a topic among many researchers and professional practitioners for a variety of reasons, which include but are not limited to: interests in developing improved collaboration practices (Holzman, 2009), efforts to create systems capable of minimising information loss between models (Coenders, 2011), or a desire to effectively enhance each individual sub-model's design contribution to the project whole through efforts to activate the interfaces between them (Kilian, 2006). This research project terms these collections of partial representations model networks.

3.2 Multi-model typologies

In his PhD thesis *NetworkedDesign*, J.L. Coenders articulates a software-based approach to normalising design design systems for managing multiple, discrete partial models within a global modelling system for architectural design and project delivery. In his exploration of existing practice, he describes current approaches to multi-model formulation as falling into two general categories. The first aims to develop projects through "single central models" and the second pursues the use of "federated models." He breaks both approaches further into "weak" or "strong" implementations, which reflect the functional or ideological stringency of adhering to the principles of each category. Here, projects managed through strong single central models are both rigidly homogenous and the rarest in actual implementation. For these models, not only is all model data expected to ultimately be captured within a single database, but the software that manages that information must also operate as the sole means to author new model data (although it may be possible for multiple distinct support models to exist as contributors to this central repository). A weak unified model then relies on a central repository as the primary – if not exclusive – means to produce project documentation and manage coordination, but allows for different software platforms to manage various model representations. A weak, federated modelling approach uses strict protocols for model interaction but does not rely on a central repository for documentation and coordination. Finally, a strong, federated modelling approach not only allows for multiple software platforms but relies on custom interfaces between them to communicate key information related to documentation and coordination. In general, as one moves from the strong form of single central models to the strong form of federated models, there are a series of spectra that describe their characteristic tendencies: a relative ease of use and collaboration moves toward greater technical difficulty, but one that is attended by increases in potential for operational specialisation, design variety, flexibility and quality. (Coenders, 2011)

An interesting alternative to thinking about the management of multi-model systems has been presented by practitioners at Skidmore, Owings & Merrill who demonstrate the use of a proprietary "platform-free software code" for maintaining "a master model that is flexible and adaptive." (Park and Holt, 2011) Their process describes the generation of an independent data management system developed to negotiate critical information across multiple parametric modelling platforms, supporting a complex building project from design ideation through construction documentation, assembly manufacture, and installation. Their master model behaves much as a single central model in that is operates as the primary "repository of various iterations and results obtained from specific analysis." Yet the information captured in this model is fundamentally transient in nature, and what they deem the master model is not responsible for producing representations related to analysis or documentation, but rather is expected to operate as a lightweight exchange system. It essentially operates as an additional layer to a "strong federated model" in that a wholly independent data store is introduced that enables the designers to capture and synthesise design information from a variety of sources outside of existing CAD-based systems, going beyond simple data exchange by introducing a mode that affords data enhancement.

Iteration, consequence and interdependence

For any given representational engine to effectively serve its purpose, it must achieve a requisite level of resolution and refinement. The process of developing any given representational engine – or partial model – is most commonly undertaken through versioning, a series of explicitly autocatalytic processes of self-re-creation, whereby one design model works as a type of scaffold in the development of a more refined instance that is ultimately used to replace itself. This process describes an iterative approach to design modelling and development that is fundamental to architectural design practice.

Representational engines are most typically organised to feed forward into consequent steps in the supply chain of the project in total. For example, a schematic design model that has defined the general volume for a building design may be consumed by various stakeholders responsible for the further development of individual systems or components at a higher level of resolution. Such a consequential method for project development may undertake a series of processes, distinct for each partial model, where: it is first produced, parameterised or otherwise informed by antecedent models; is then developed through iterative or step-wise processes; and lastly is used to generate new representations that feed forward as it produces, parameterises or otherwise informs the development of sequentially dependent models.

An alternative modelling methodology approaches model development with an aim to toward cultivating interdependency between representations within – and sometimes across – projects. The types of representational engines implemented using this approach are characterised by recursive logics, feedback loops, and multi-directional constraints that operate between partial models – both consequent and antecedent – such that the information production that they contribute to is inextricably tied to these relationships. For these types of partial representations, the focus on the parameter spaces that exist between them take primary importance, because it is through these information thresholds that they communicate with one another and activate their bi-directional constraints.

Bi-directional constraint modelling

This focus on the interfaces that exist between model elements is reflective of this research project's interest in furthering state-of-the-art methodologies for creating more dynamic parameter spaces in algorithmic design models. model networks within the same framework of the "bi-directional modeling of constraints" that have been articulated through Axel Kilian's PhD research project.

Kilian frames his work in some ways as a critique of the strict, protocol-driven interests that govern single-central model approaches, and which he claims restrict innovation in design discovery. He asserts that “the software industry gets routinely stuck in its attempt to define the next industry standard for interoperable, three dimensional, building information modeling, parametric, file standard.” His claim here is that such systems have a calcifying effect on the designers expected to employ them. He suggests an alternative focus on an intensively platform-agnostic approach to project development that identifies the local problem spaces individual representations are expected to address as the chief drivers for systems development. The primary mechanism that Kilian aims to privilege lies in the “dependency networks” that exist between discrete model representations; these in turn are made interdependent through the establishment of bi-directional constraints.

These types of constraints suggest that while each individual model element has its own responsibility in terms of producing important design information, it is explicitly driven according to terms that are defined in a different domain. (Kilian, 2006) An experiment central to this research project focused on the digitisation of hanging chain models, establishing at the time a new precedent for simulation-driven computational design modelling. In an approach that has since become more common, topological constraints are introduced through the definition of a connectivity graph that describes the relationships between what will become the constituent elements of the overall form, and material and the application of physical constraints that are activated through a physics-based simulation model on this underlying data structure. In this way the model topology and the digital representation of the chains’s material behaviours are tightly bound to one another through a process of simulation. (Kilian and Ochsendorf, 2005)

This general approach that locates dependencies between multiple representations points to the use of an ecology of models that reflects a “system design” with an “holistic design goal and self-referential dependencies among its parts.” (Kilian, 2006)

Toward a holism of ideation and functional output

A chief aim for architecture – especially in the context of a digital-material practice – is ultimately to clearly communicate a set of ideas through built artefacts, however abstract or formally driven that conceptual motivation may be. For a digital-material practice engaged in design-led experimentation – either within a research-based or professional environment – theoretical knowledge production and making are tightly bound to one another.

Architectural representations that then synthesise the production of functional output in support of the realisation of a given design brief with the effective communication of the animating processes of ideation related to the conceptual content of the project become powerful instruments for digital-material practices.

A primary stated goal of this thesis is to describe a methodological framework for digital modelling that synthesises the support of "designerly thinking" – of encouraging processes of invention and discovery – more closely with the mechanisms for creating and managing form and organisation, performance analysis, assembly systems resolution and specification, fabrication and installation. A better understanding of the synthetic performance of a model network should then be explored according to its holistic behaviours.

3.3 Holism

Prior to the 20th century, studies in biology focused on a reductionist or mechanistic view of a given subject's fundamental characteristics or behaviour. Such an approach assumed that by breaking the components of a subject of investigation into smaller pieces and studying the mechanisms of its underlying individual action and purpose, one would be able to define for each a scale at which its purpose and effect on the larger system in question could be grasped, defined and articulated. Atomising systems into their component elements for a thorough investigation and then "reassembling the whole from the behaviour of the pieces" was then believed to be the best means to describe the system. (Trewavas, 2006) In such systems, both inputs and consequences would typically be understood as ultimately being linear, uni-directional, or predictable in nature. Especially from the 20th century, however, several biologists began to fundamentally question this approach. One of the earliest to do so was Jan Smuts, who in 1926 first articulated the idea of holism as an approach to understanding biological systems. His definition of holism depended on the assertion that no single component within a larger system could be properly understood when considered as an independent entity, but rather must be examined for its structured connections to elements on which it was either dependent or interdependent. Most especially, he considered it crucial that the consequences of these interdependencies to the phenomenology of the entire system was essential not only to any fundamental understanding of it in total, but also of the definition of each constituent element. It is therefore especially important then that sub-elements or assemblies within a larger ecology must be considered beyond their individual, discrete functionality.

This idea is closely tied to the assertions that:

1. The global behavioural effects or actions for a system under inquiry emerge from interactions between internal sub-systems or components, as well as with external systems or contexts with which the system under inquiry interfaces.

2. Even as sub-systems or components contribute to global behaviours, they must also be understood as being partially controlled by the effects to which they contribute. As a result, many inputs that may drive the future state of a given system are auto-catalytic in nature, as the system in total exhibits the capacity for self-interaction and feedback loops.

Central to this work is a formulation of "systems thinking" for both the potential complexities embodied in the network of interdependencies between sub-systems and external effectors in larger collections, and also for the compounding effects on performances that collections of individually complex components frequently demonstrate when working together as part of a whole. Understanding that the overall performance of a system is "greater than the sum of its parts" is a primary characteristic for holistically considered entities:

> *"The whole thus appears as a marked power of regulation and co-ordination in respect of both the structure and the functioning of the parts. This is probably the most striking feature of organisms – that they involve a balanced correlation of organs and functions. All the various activities of the several parts and organs seem directed to central ends; there is thus co-operation and unified action of the organism as a whole instead of the separate mechanical activities of the parts. The whole thus becomes synonymous with unified (or holistic) action."(Smuts, 1927)*

And although Smuts developed his argument through biology and with an aim to support its understanding through Darwin's Theory of Evolution, he was clear to point out that "the idea of wholes and wholeness should not ...be confined to the biological domain; it covers both inorganic substances and mental structures as well as the highest manifestations of the human spirit." And indeed applications for the study of the behaviour of complex systems have become nearly ubiquitously deployed as a focus of research across a great variety of scientific disciplines. Indeed, the further abstraction and study of systems became the focus of specific, generalised scientific inquiry in the middle part of the 20th century. Its arrival as its own explicitly declared discipline is located in the 1950 publication of Ludwig von Bertalanffy's *An Outline of General System Theory*, wherein he began to lay out its theoretical basis. He sought to identify "general systems laws" that would address a clearly identified "need for a general superstructure of science" that extended this manner of thinking about interdependence in complex systems beyond biology and into hierarchies of antecedent and consequent scale:

> *"Reality, in the modern conception, appears as a tremendous hierarchical order of organised entities, leading, in a superposition of many levels, from physical and chemical to biological and sociological systems." (Bertalanffy, 1950)*

Both Smuts and Bertalanffy speak about holism as a means to understand the unified nature of complex systems and their sub-assemblies (Smuts in fact derives the term "holism" from the Greek for "whole"). They assert here simply that any subsystems required for the production of a specific set of phenomena do not contribute to their emergence as individual elements, or at any rate cannot exert influence as independent agents. The emergent phenomena produced must instead be understood according as much to the catalytic relationships between sub-systems as to the internal qualities and purposes of them as individuals. Unification – what Smuts referes to as "unified (or holistic) action" – here then describes the synthesis of systems in producing emergent phenomena:

> *"The fact that certain principles apply to systems in general, irrespective of the nature of the systems and of the entities concerned [helps explain] concepts such as wholeness and sum, mechanisation, centralisation, hierarchical order, stationary and steady states, equifinality, etc., [which] are found in different fields of natural sciences." (Bertalanffy, 1950)*

3.3.1 Modes of unification

Specifically, the type of systems unification that is being addressed in these works is one that considers the relationships between heterogeneous parts for the means by which they catalyse the characteristics of emergent phenomena. It is the differentiation not only of the elements within these systems, but also of the natures of relationships between them – and their effect on overall system behaviour – that becomes central to their investigation. At each stage a general-systems understanding of unification is then tied to the principles and processes that describe interactions between constituent, fundamentally discrete and heterogeneously formulated elements. Model networks for digital-material practice in architectural design and project development are appropriate targets for this epistemological framework. As discussed in the Introduction to this dissertation, modelling technologies continue to proliferate at an accelerating pace, affording architects and other stakeholders for design projects new opportunities for creating specialised representations for an increasing variety of concerns: the tools and approaches at our disposal become increasingly heterogeneous in their makeup, and their combined application increases in its potential for complexity.

However, for certain contemporary architectural practices, this critical focus on the heterogeneity of component elements is at odds to methods for computer-aided design modelling that are animated instead by a desire for homogenisation. This occurs despite an implicit understanding that the varied functional purposes of modelling systems necessarily remain fundamentally heterogenous in nature, even within such restrictive frameworks as a "strong single-central model" as articulated by Coenders. In discussing digital modelling methodologies, homogenising unification can be understood both ontologically and axiologically. Ontologically, *instrumental homogenisation* can be generally characterised according to its focus on the non-task-specific application of strict protocols, rigid data structures, and for the privileging of the role of and movement toward "master" design modelling systems. As much as possible, instrumental homogeneity in digital modelling seeks to locate as many processes within a single software platform environment – or even a "single source of truth" model – with a focus on uniformity in data structure. Axiologically, *ideological homogenisation* may be characterised as asserting an orthodoxy for applying a specific methodology or theoretical reasoning. Both types of homogenisation are reflected in the types of "all-seeing, all-dancing" modelling solutions that Maver warned against at the 1995 eCAADe conference. In this context, homogenising approaches have a tendency to suppress, obfuscate or ignore any necessary deviations from its stated ideal. Apart from the risk of intellectual dishonesty, this failure to pursue methodologies that aim for the flexible inclusion of alternative modelling approaches, systems, or platforms may result in limited or inefficacious performances.

Examples for homogenising approaches to modelling practices are apparent in many contemporary implementations of Building Information Modelling (or BIM). Building Information Modelling describes the process of digitally producing "accurate virtual models" that accommodate "many of the functions needed to model the lifecycle of a building, providing the basis for new design and construction capabilities." (Eastman et al. 2011) BIM is most typically described by practitioners as a methodological framework and is articulated as a *process* rather than any specific *technology*. However, in practice, its application is frequently attended by a strong adherence to established or common data protocols, specific software modelling platforms with intrinsic data management constraints, and information storage or transfer procedures that favour specific file formats. In this vein, BIM defines *interoperability* as the "exchange of data between applications, which smooths workflows and sometimes facilitates their automation." (Eastman et al. 2011) For BIM, interoperability typically relies on pre-defined file formats to achieve this. Some earlier formats included the Drawing Exchange Format (DXF) or Initial Graphic Exchange Specification (IGES), which largely supported the translation of geometric specification across modelling platforms. Other protocols that have more recently gained broader adoption in practice include the Industry Foundation Classes (IFC) or SIMSteel Integration Standard Version 2 (CIS/2), both of which enable the transfer not only of geometric representations of designed objects, but also the attachment of attendant semantic data labels that specify object properties.

Much of the reason for this homogenisation is centred around the expectation that reliable, shared protocols introduce important efficiencies and potentials for improved practice into modelling practice and project development. The argument is that when stakeholders can expect information to be delivered in a consistent format, it enables them to prepare repeatable frameworks or templates for information processing. Even if there is a great deal of truth in these claims, there remains a risk in applying a rigid orthodoxy to model development, especially regarding the application of strict protocols for information across the model network. A chief concern lies in how strict protocols limit the types and variety of information that may be shared between partial models in a network. Homogenising protocols are by nature rigid, and are generally restrictive to designers who aim to invent or adapt new information structures that may be applicable to a customised design system.

3.3.2 Network formulation

Representational engines have been described according to how they may interface with other elements within a network – whether they are consequentially or interdependently linked to them – and also have been characterised according to their own iterative development. The practice of building up a complex model network is almost invariably a non-linear process, with expectations and requirements for the functional purpose of each representation as well as the information being passed between adjacent elements evolving over time. This is especially true for open-ended design systems such as Peter Cariani characterises, when the designer begins the process with incomplete knowledge across as an array of concerns: the problem may be ill-defined, and observable parameters, desired actions, and coupled controls may be riddled with unknowns. (Cariani 2008)

The highly prescriptive nature endemic of homogenising approaches to model formulation tends to have limited value in open-ended design contexts, because their constraints are based around very clear goals. For many components within a model network, this may be highly appropriate: if the target outcome for a given representational engine is a traditional drawing set, then many of the protocols that are prescribed through Building Information Modelling regarding specifications, standards, and data assignment may be perfectly appropriate. However, if for example within the same project there is an aim to develop a series of more dynamic relationships between form, structure, and expected use – and each of these design pursuits is being developed through a collection of interdependent partial models which are parameterised according to constraints formed across these different design interests – then the information drivers for each of these is likely not only to be bespoke to the project, but also must be expected to evolve as each model's iterative formation is undertaken.

The improved holistic performance of the model network then becomes inextricably tied to the quality and flexibility of the information thresholds that exist between its most interdependent constituent elements. In contrast, those elements that are more consequential in nature and predictable in their requirements – those which consume data in a more reliable or repeatable fashion – have less potential to compound increased design intelligence. This distinction refers back to arguments made for considering differently *computation* versus *computerisation*, whereby application of the former affords the designer the potential to increase intelligence for a target desk system, whereas the latter reflects an approach better suited to capture or record knowledge which already exists.

In practice, while both computation and computerisation may be essential for the design and delivery of complex projects, computational approaches that are executed through increasingly interdependent relationships between constituent partial models afford greater potential for exhibiting open-ended *knowledge producing* behaviours. If homogenising approaches to establishing data relationships tend to rely on strict or rigid protocols to achieve interoperability – supporting effective translation across modelling platforms for geometric object representations which may additionally be coupled with descriptive data labels – and so are generally effective for data capture and communication, then the question arises: how might information transfer be most effectively defined for partial models that are fundamentally interdependent with adjacent elements?

3.4 Adaptive data structures

One of the benefits of using more homogenising approaches to model formulation is that the underlying data structures that they rely on tend to be predictable. As previously discussed, however, they also tend to be restrictive and inflexible. In *What Technology Wants* Kevin Kelly discusses the value in similarly shared or agreed upon protocol-driven communication frameworks, but with some crucial differences. Here he refers to both spoken and computer programming languages. These types of frameworks are once predictable, robust and flexible, allowing for the articulation of very general concerns. The information thresholds that help activate and constitute the holistic behaviours of model networks – especially those that aim to produce open-ended design solutions and produce new design intelligence through feedback loops and computation – share this same aim.

This dissertation has described adaptive parameterisation as a means to formulate modelling setups that facilitate the dynamic activation of mutable substrates. Mutable substrates aim to work as adaptive data structures that support the adoption and application of flexible or general concerns: they should provide enough stability in form and predictability to effectively negotiate the information thresholds that bind multiple partial models together while simultaneously facilitating the execution of each partial model's discrete purposes. Likewise, they should be changeable enough to support iteration in the creation and refinement of a given partial model's mechanistic or instrumental makeup. They furthermore should enable bi- or multi-directional constraints between partial models, as recursion and feedback loops instantiated between each are employed to increase design intelligence, and which in turn may aim toward design models exhibiting a form of epistemic autonomy in their holistic performances.

In the formulation of model networks, the modeller has traditionally been charged with explicitly setting the boundary conditions for the parameterisation or feature spaces that bind partial models, as well as to their relationships to the algorithms and computational methods that they inform. This research identifies multiple dynamic or adaptive parameterisation techniques as demonstrated means to activate increasingly nuanced deployments of model networks in computer-aided design. Through the experimental interrogation of parameter spaces within complex models in a digital-material practice, the publications that follow this chapter follow this research project's pursuit for these types of data structures.

For the publications that support the research projects *The Rise* and *Learning to be a Vault*, the model setups and supporting data structures are discussed in some detail. For both of these projects, the approaches to creating the mutable substrates that supported algorithmic dynamic activation were largely specific to each given project. However, throughout this research project an interest in the representational potential for meshes has been maintained. For the research project *Stressed Skins*, a more generalised framework for the articulation of heterogeneously formulated model networks is applied, based on the application of half-edge mesh data structures. In addition to the exploration and discussion of this project in the relevant following publications, an introduction to mesh-based data structures and their suitability for supporting adaptive parameterisation follows here.

3.4.1 Mesh-based data structures

Polygonal mesh representations of geometry are generally captured through data structures that are: light-weight in terms of memory storage; easily traversable in terms of their ability to describe relationship adjacency or localised geometric qualities; and highly extensible in terms of having custom attendant data attached. A *mesh* most generally describes a collection of one or more polygonal faces whose configuration may be used to represent a target geometry, either as a duplication or approximation of its form. For example, any object comprised of one or more planar elements may be precisely reproduced, such as a tetrahedron whose collection of four distinct triangular elements may be virtually duplicated. Any surface or solid object with curvature may be approximated to specified levels of resolution through a subdivided collection of multiple triangles whose vertices lie on the geometry being represented. Triangulated meshes – those whose underlying faces are always composed from three corners or vertices – are a historically common type of mesh representation because of their relative simplicity, flexibility in geometric representation, and functionality for analytical techniques.

Visualisation

Triangulated meshes have played a central role in CAD systems that render 3D geometry to a screen or monitor, at least since 1967, when some of the first engines for visualizing surfaces or solids were developed using mesh-based techniques, such as by David Evans and his team at the University of Utah and by Arthur Appel at the IBM Research Center. (Weisberg 2008) Despite their age, mesh-based geometric representations remain central to nearly all contemporary computer-based modelling or visualization systems that represent 3D surface or solid geometries. Although many contemporary CAD modelling systems internally rely on highly precise mathematical representations of geometries, through such mechanisms a non-uniform rational basis spline (NURBS) surfaces, or geometrically-driven constructive solid geometry (CSG) modelling techniques, for their visualisation such idealized mathematical representations are almost universally first converted into mesh-based data structures. These mesh-based representations are then typically translated to a screen or monitor through graphics processing units, using shaders (such as OpenGL or Direct X) to represent different material or light-based characteristics, depending on the specifications or virtual conditions in which the mesh is present; in this way, modellers that use non-mesh-based approaches to geometric generation nonetheless maintain both an internal "idealised" geometric format as well as a mesh-based approximation for visualization. Mesh-based data structures are effective enough at these purposes that even today they largely follow similar processes as those originally configured in the mid-1960's (albeit with the benefit of significant advancements to both computational power and algorithmic efficiencies for rendering).

Analysis

In addition to their near ubiquity for visualising geometry, it is noteworthy that the use of meshes as analytical instruments in fact precedes their application in 3D computer graphics, with triangulation-based representations of complex geometries being used in the development and application of the Finite Element approach. In the early 1940's, the engineers Courant and Hrennikoff first identified the value in discretising continuous domains into mesh-based representations for making the step-wise calculation of elastic material behaviours more tractable. While their calculation methods ultimately differed from those that eventually became more established, they pioneered the use of meshes as the data structure applied in their framework. The contemporary approach to finite-element analysis was first fully articulated as a means to model similar material-specific structural behaviours by M.J. Turner in 1952 (although the term "Finite Element Analysis" which described the discrete mesh faces was not coined until 1957). Finite Element methods were later generalized to describe various other material behavioural properties (such as heat exchange, for example) by O.C. Zienkiewicz and Y.K Cheung in 1965. (Gupta and Meek 1996). In all cases, triangulated representations of geometric elements were essential to both the geometric description of the target system and the predictive simulation of their expected behaviour under different loading or physical conditions (both for surface-based techniques as triangular faces and in solid-based representations as tetrahedral volumes).

Face and vertex collections

Meshes manage these analytical requirements through the potentials embedded in their data structure. In its simplest form, a mesh's underlying composition may be captured with each of its polygonal faces being defined through the specification of its constituent corner points, or vertices, where each vertex is designated as floating-point coordinate values for its position in Cartesian space (X, Y and Z values). From this base representation, most mesh-based data structures are formulated differently to better support the traversal or transformation of its constituent faces and enable it to store additional data for better functioning in other operations, such as in the local application of material characteristics to assist in visualisation or simulation.

Most mesh data structures rely at the very least on single mesh objects being defined through two distinct but interdependent collections: one collection to store vertices, where each vertex is designated with floating point coordinate values for its position in Cartesian space (X, Y and Z values), and the other collection specifically for faces, where each face is assigned indices according to the corner count in its polygonal form, one for each of its constituent vertices. This simply-extended face-vertex data structure enables programmers to more easily "traverse" the mesh, as searches based on integer-based vertex indices are less computationally expensive to perform, so, for example, it becomes simpler to identify edges shared between faces. Many contemporary CAD-based software platforms maintain a proprietary variation on this mesh-based data structure that is customised to extend these logics in different ways to better manage visualisation, storage, or rapid derivation from more ideal numerical descriptions of geometric objects, depending on the platform's particular needs. It is this searchability that makes meshes so instrumental to analytical techniques like the finite element method which rely on the step-wise determination of behavioural changes for each face or vertex in relation to one another.

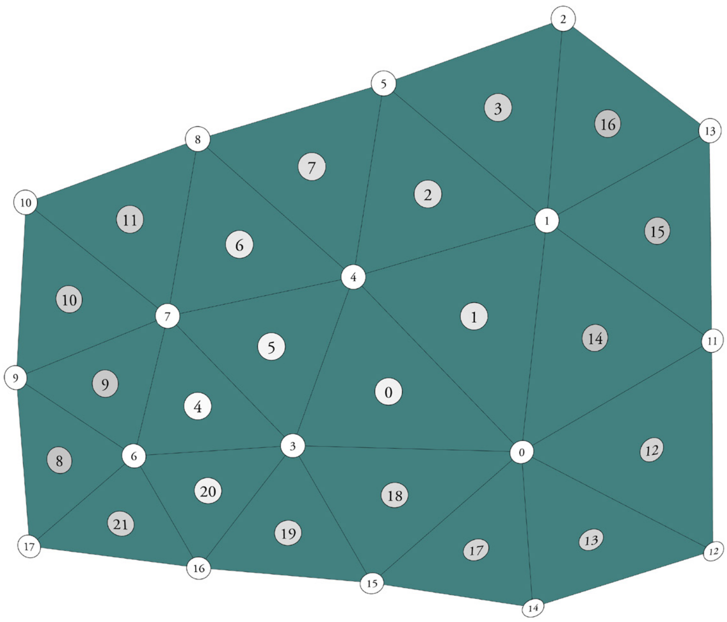


Figure 1: Example layout of a Face/Vertex triangulated mesh with index mappings of faces (in light gray) and vertices (in white). Here, *Face 0* is comprised of *Vertices { 0, 3, 4 }*

Topological transformation

A mesh's ability to provide basic geometric representations or support analytical techniques by capturing important connections between underlying elements is enhanced by their capacity to undergo topological transformation according to different user-supplied specifications. The relationships that exist between different components of a mesh – its faces, vertices, or edges – is referred to as its underlying topology. Unlike mathematical topology, which is concerned with the spatial properties that persist despite certain transformative operations – such as stretching or twisting – mesh topology can be better understood as describing one (or more) node-edge graph networks. Vertices, for example, are connected to one another by edges, and faces are connected to one another across shared edges. Euler operations enable the transformation of these underlying relationships while preserving the overall boundary conditions of the mesh. Such operations either "decimate" the mesh by reducing its resolution (as related to face count), or "refine" it, by introducing new faces. (Vorsatz, Rössl, and Seidel 2003)

Figure 2: Half-edge mesh representations introduce explicit edge indexing, where each edge is split into a pair of *half-edges*. Each half-edge is parameterised with indices for the *face* it is a part of, its *start vertex*, the *previous half-edge* on the same face, and its *opposite half-edge*. These definitions facilitate *Euler operations* that may be performed on a mesh by allowing for these transformations to remain relatively localised. This minimises both the need for re-indexing and also the computational expense of doing so when required.

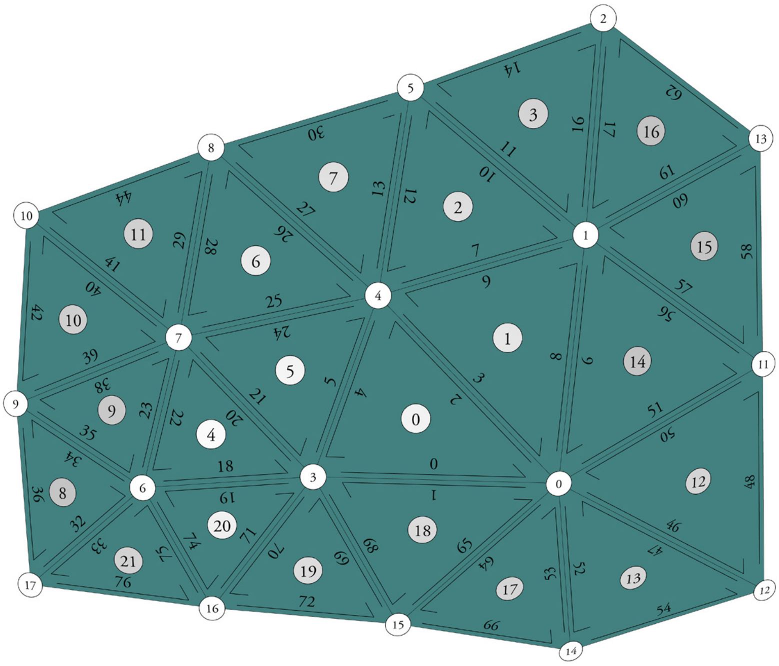
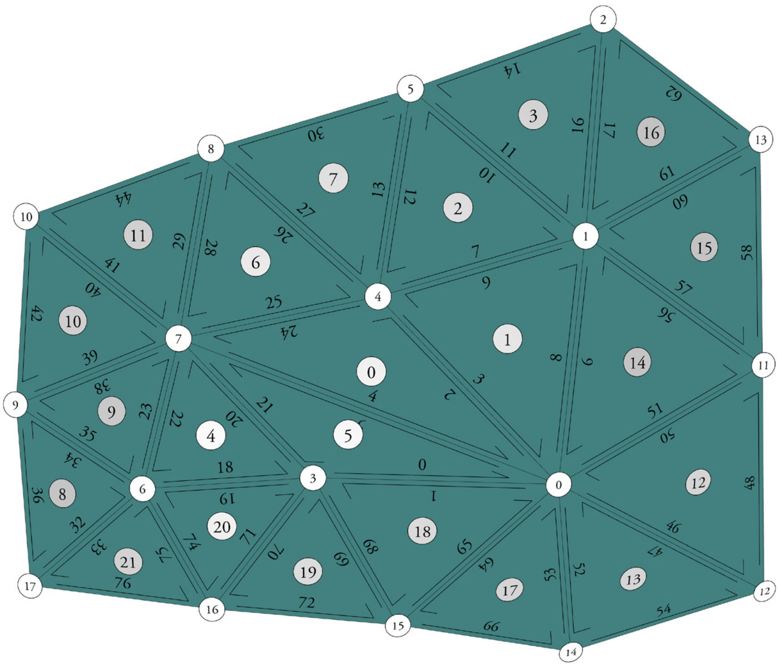


Figure 3: *Edge flipping* within a triangulated half-edge mesh results in a reorganisation of the half-edge specified for the flip operation, where its and its opposite half-edge start indices are shifted to the start index of their respective *previous* half edges. In this example the half-edge pair indexed 4/5 is flipped. Edge-flipping supports refinements toward more optimal vertex valences (in triangulated meshes, vertices that connect six edges are considered "optimal" for regular or well-balanced)



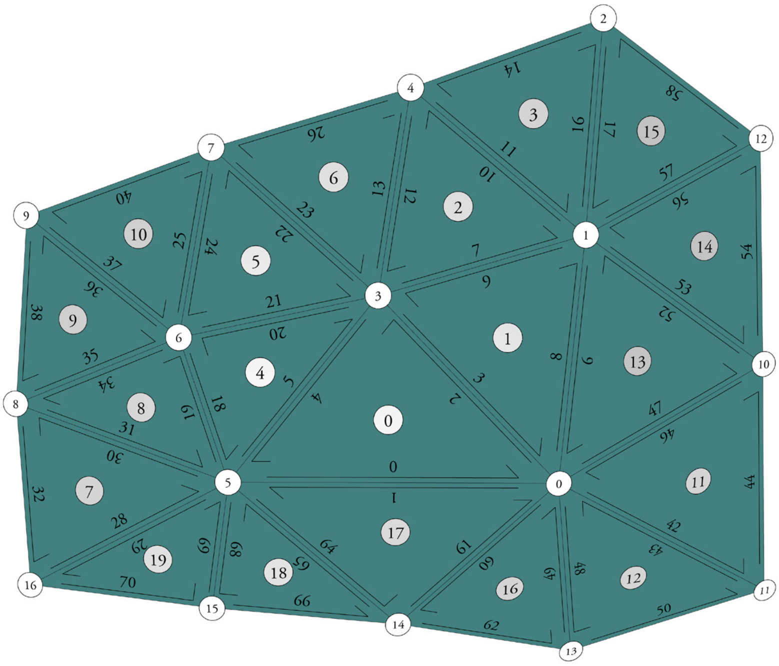


Figure 4: The *local decimation* of a half-edge mesh can be achieved through an *edge-collapsing* Euler operation, where the extraction of a half-edge pair results in the removal of two faces. In this example, the half-edge pair 18/19 from Figure 2 is collapsed. Collapsing operations are used when a locally coarser approximation of geometry may be acceptable for the desired representation.

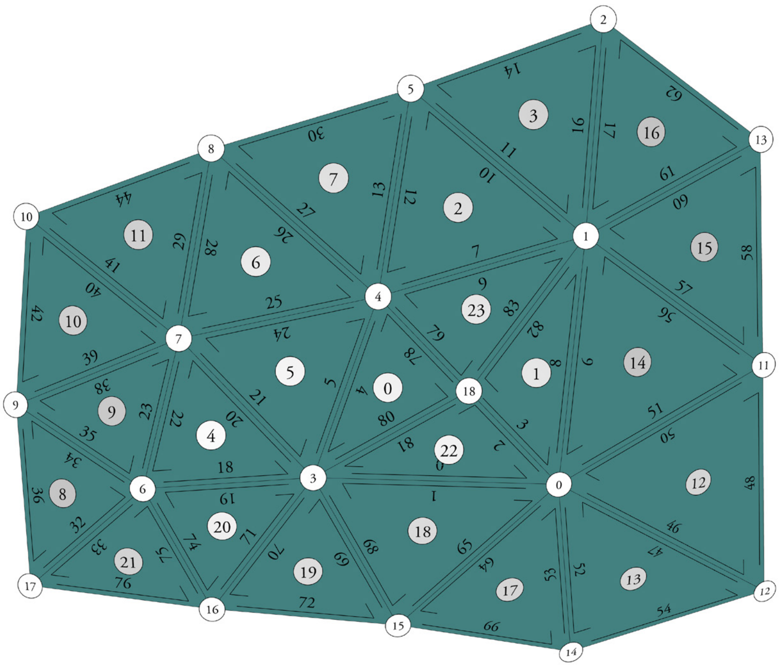


Figure 5: The *local refinement* of a half-edge mesh can be achieved through an *edge-splitting* Euler operation, where the introduction of a new vertex in a specified half-edge results in two faces being split into four. In this example, the half-edge pair from 2/3 are split. Splitting operations are used when a locally more refined approximation of geometry is desired to improve the resolution of representation.

These transformations to a mesh may be used to achieve a variety of goals. For example, because both the amount of memory a mesh takes up as well as its potential to more correctly describe geometry (especially complex, curved geometery) is dependent on its resolution, it is frequently desirable to create mesh representations whose resolution is curvature adaptive. (Miller and Stasiuk 2017) Curvature adaptive meshes have their resolution locally varied, with higher polygonal density in areas of high curvature and lower polygonal density in areas of low curvature. This variation in resolution may be calibrated according to an allowable local error from the idealised geometry. (Dunyach et al. 2013) In addition to curvature adaptation, there are a variety of applications for such locally varied mesh resolution. In finite element analysis, for example, it is frequently desirable to have higher-resolution meshes at the interface of different elements, or at locations where there is an expectation for high levels of energy transfer.

Half-edge meshes

The half-edge approach to structuring mesh topology was first presented in 1978, where it was described as a double-connected edge list (DCEL) (Muller and Preparata 1978) Half-edge meshes differ from the standard face-vertex representation of a mesh in that they explicitly organise the mesh representation based on edge indices. Here each edge is split into an edge-pair of half-edges, each running in opposite directions along the same line. Half-edges are organised in anti-clockwise winding order around each face, such that each face may be defined by the direction and sequence of its composite half-edges. Each half edge then stores four key data points: 1) the index of the "edge pair" that it runs opposite to, 2) the vertex index at its starting point, 3) the face whose winding order it helps define, and 4) the index of the "next" half-edge that shares the same face with it. While this introduces an additional layer of information that must be explicitly stored in memory for a mesh, it reduces the computational expense of performing extensive topological transformations to the mesh by tracking a broader range of relationships between entities.

For example, from these four key data components, topological traversal of the mesh is vastly simplified, especially for the performance of Euler operations on the mesh, which include such actions as "flipping" edges, "collapsing" edges, or "splitting" edges. In contrast to a face-vertex meshes where edge-relationships must be recalculated across the entire mesh following each Euler operation, half-edge meshes enable many refinement operations to be performed before indices must be recomputed – or "compacted" – after refinement or decimation.

This broad support for topological transformation may be coupled with the capture of additional local descriptive data for a given element within the mesh (a face, edge or vertex, for example). In this way becomes possible for design meshes to directly engage in material simulations that rely on localised parameterisation across different elements within the mesh, even while their topologies are dynamically adjusted according to rule sets that they evolve over time. Such open-ended systems enable robust feedback loops either intrinsic to the partial model in which the operation is being performed, or even across multiple partial-model representations, each of which may be engaged in executing its own step-wise calculations over time, and (re)constraining each other. By so considering the mesh topological space as an environment for the passing of information from location to location, it is possible to better calibrate it for complex architectural expressions in form, simulated behaviours of material, specification, and production of assembly systems. This dual application of meshes for their ability to capture both geometry and behavioural properties helps identify them as useful data structures for operating as mutable substrates in processes of adaptive parameterisation.

3.5 Conclusion

This chapter has explored model networks in relation to their role in contemporary architectural project development. Considering that architectural projects are developed and realised through collections of "partial representations", contemporary approaches that principally implement computer-aided-systems may be considered as networks of partial models, or model networks. This chapter has further articulated that understanding how networks of partial models work in conjunction with one another – and furthermore that development methodologies to support their improved performances – is a topic of great interest, and central aim for this research project.

In the examination of multi-model typologies, this chapter has explored different approaches to the synthesis of discrete elements within model networks. Through iterative practices, individual partial model may be recursively developed through a versioning process where each new instance relies on a prior, less-resolved instance for its advancement. Depending on each partial model's role, they may then be set up to work in conjunction with

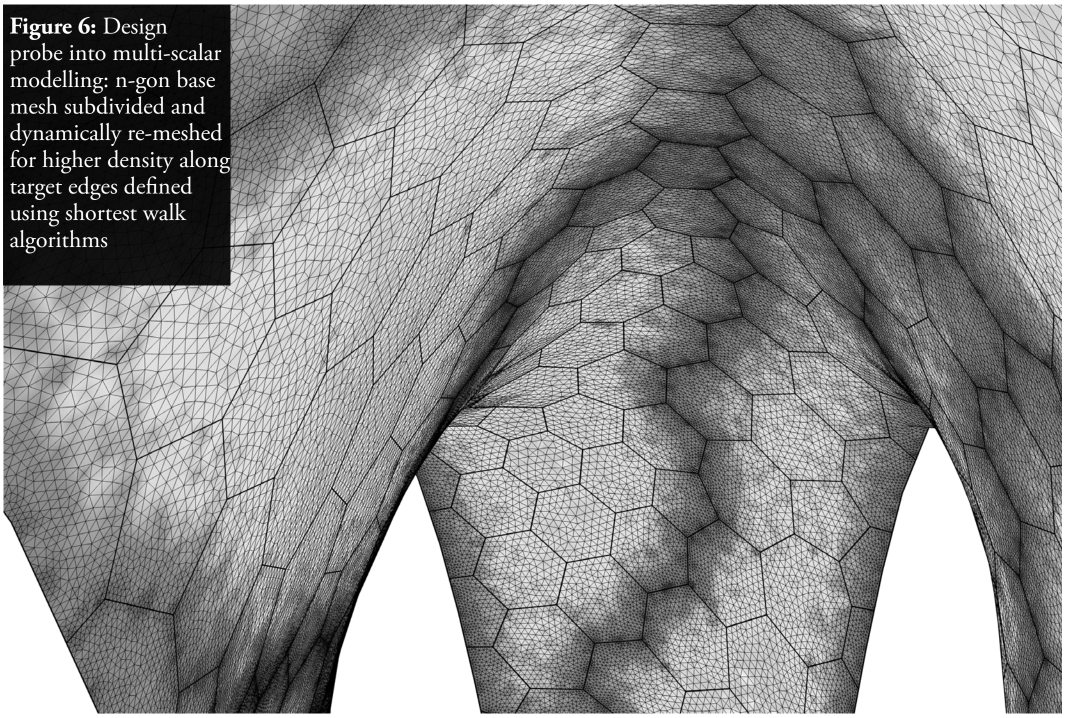
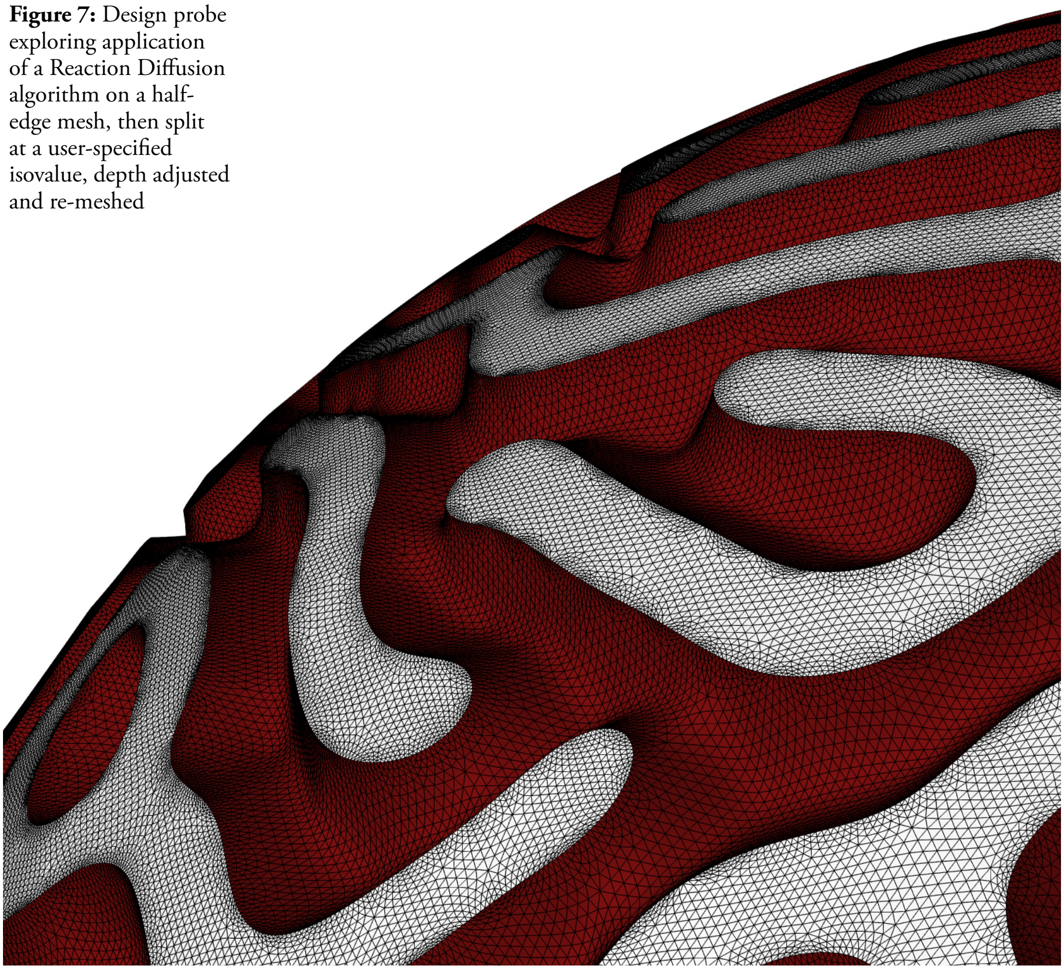


Figure 6: Design probe into multi-scalar modelling: n-gon base mesh subdivided and dynamically re-meshed for higher density along target edges defined using shortest walk algorithms

Figure 7: Design probe exploring application of a Reaction Diffusion algorithm on a half-edge mesh, then split at a user-specified isovalue, depth adjusted and re-meshed



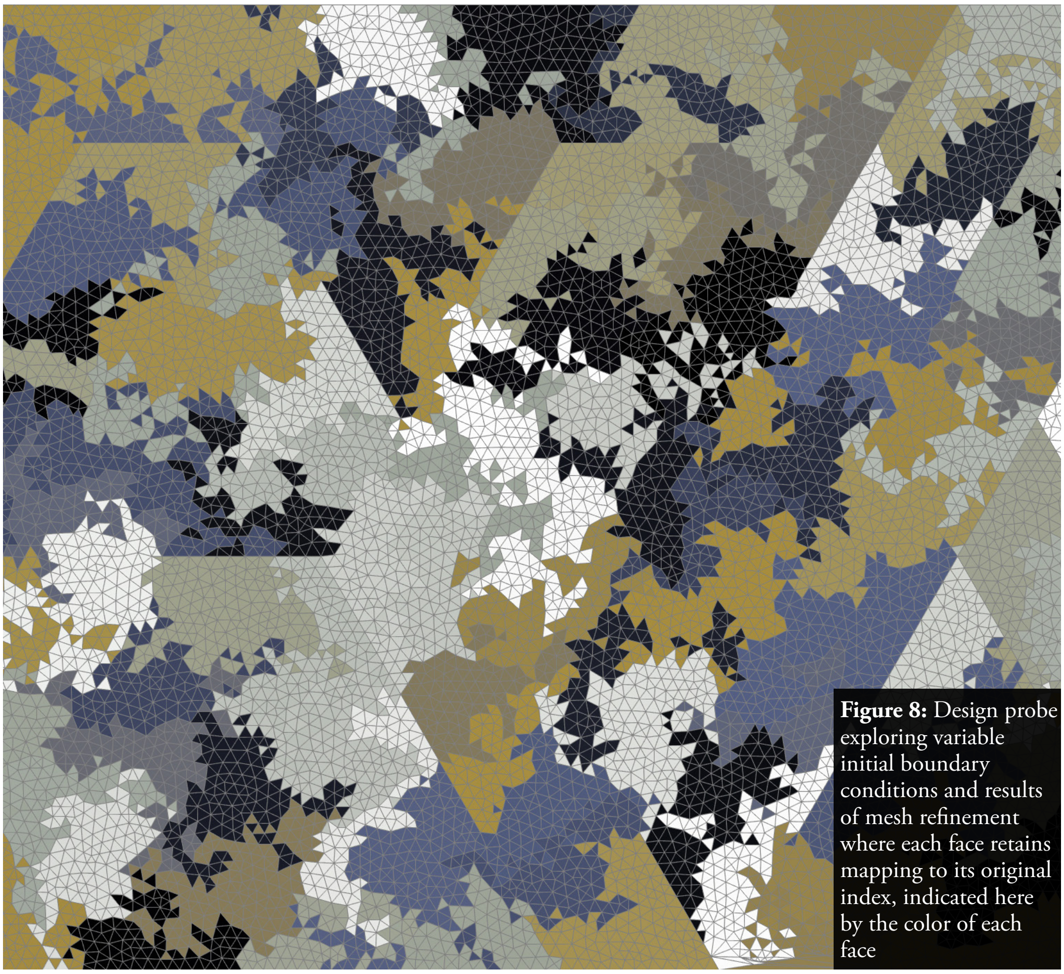


Figure 8: Design probe exploring variable initial boundary conditions and results of mesh refinement where each face retains mapping to its original index, indicated here by the color of each face

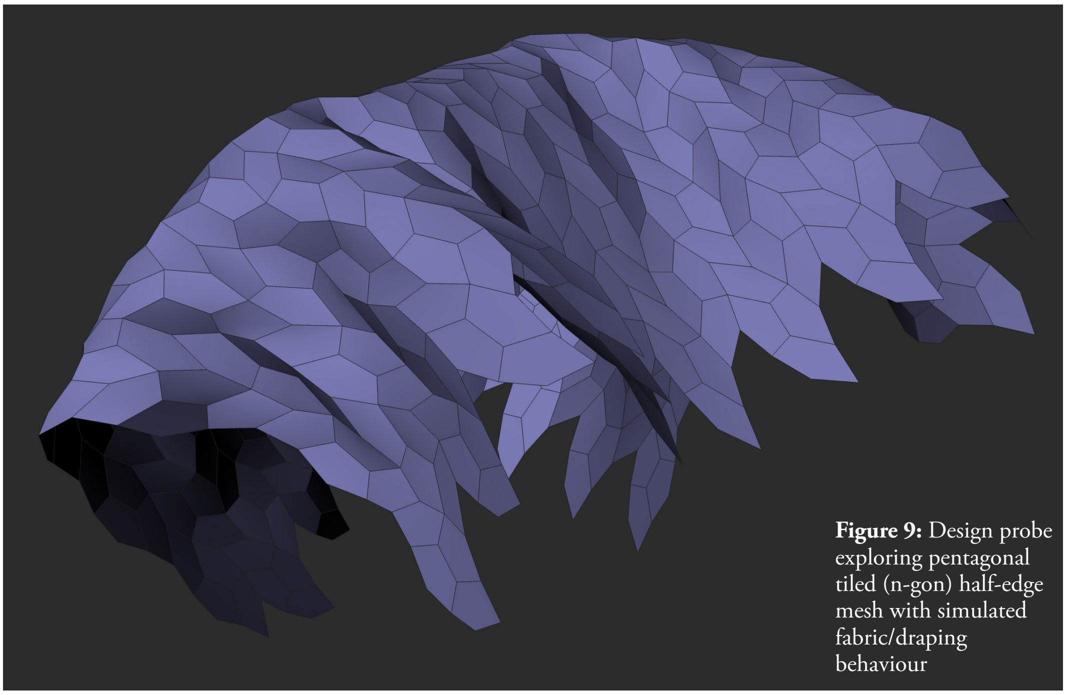


Figure 9: Design probe exploring pentagonal tiled (n-gon) half-edge mesh with simulated fabric/draping behaviour

adjacent models either through consequential or interdependent relationships, based on each model's functional purpose. This research project aims to support the claim that the promotion of increased interdependence between underlying model elements endows model networks with improved abilities to increase design intelligence, and referred to precedent studies and research into how such bi- or multi- directional constraint modelling approaches are effective for improved design outcomes. Because model interdependence depends on the information thresholds that exist between partial model elements, this chapter has examined both rigid and flexible approaches to model organisation, based on different protocols for interaction and information exchange between partial models. It has taken the critical position that methods which promote more homogenous protocols may be inherently limiting in contrast to those that support more heterogeneous types of information exchange.

It has identified holism as an effective device for considering the global behaviours of model networks based on the global performances that are introduced not just according to the output of each constituent partial model, but especially according to how they work in conjunction with one another. It has explored holism and general systems theory to unpack how the relationships between discrete elements within complex systems become central to this global behaviour. For model networks, these relationships are here examined, and reassert the importance of the role that information thresholds play in eliciting increasingly interdependent behaviours from underlying model elements. This chapter has re-introduced adaptive parameterisation as a flexible and general methodology for model formulation that directly supports this and promotes improved holistic performances from model networks.

Adaptive parameterisation as defined in this research project relies on model setups that enable the dynamic activation of mutable substrates. Here, dynamic activation refers to some algorithmic or procedural process that computes new intelligence about the target design system, and a mutable substrate reflects a data structure whose topology may be flexibly altered to capture this intelligence and successfully leverage interdependence between discrete model elements. These improved feedback loops create catalytic relationships between discrete model elements that may lead toward a form of epistemic autonomy in the behaviours and performances of model networks. This definition of a mutable substrate is intended to be both general and non-restrictive, and for several of the major experiments presented in the publications that follow this chapter – such as *The Rise*, *The Social Weavers*, *The ACADIA Rise*, and *Learning to be a Vault* – custom data structures germane to each project's model network have been developed as mutable substrates to endow them with this ability to internally exchange information between partial models. Through the findings of these projects, this research project has also more broadly explored the use of mesh-based data structures as an effective demonstrator for the approach, and the application of meshes for their potential as mutable substrates is central to the experimental project *Stressed Skins*, which is detailed in the final two peer-reviewed publication submitted as part of this dissertation. In support of these findings, this chapter has therefore explained how mesh data structures work in general, and what makes them particularly suitable for their application as mutable substrates.

The publications presented in the following segment of this thesis reflect the body of experimental research that has been both driven by and contributed to the interests, motivations, and theoretical framework that has been presented in this and prior chapters. Importantly, the term *model network* as defined in this initial framework is rarely used in describing the modelling the systems employed in each of the experimental projects discussed in these publications. The reason for this is that this term has emerged as a product of the research project. Understanding parameter space and formulating it as an adaptive or mutable substrate has been an important driver of theoretical development throughout the project, as has recognising that multiple, interdependent systems must work in concert with one another to create more effective and productive, interdependent feedback loops. For these experiments, the definition of these differential systems is frequently framed in terms of the different algorithms that have been implemented or deployed for the development. Each algorithm, or computational function, in these instances, should be understood as a discrete partial model, because both its input and output parameters describe a dynamic information threshold. So it has then been in synthesising the findings from each experiment, and in identifying how other researchers have framed "multi-model" environments and concerns for interoperability that an explicit description of their makeup as networks of partial models has emerged.

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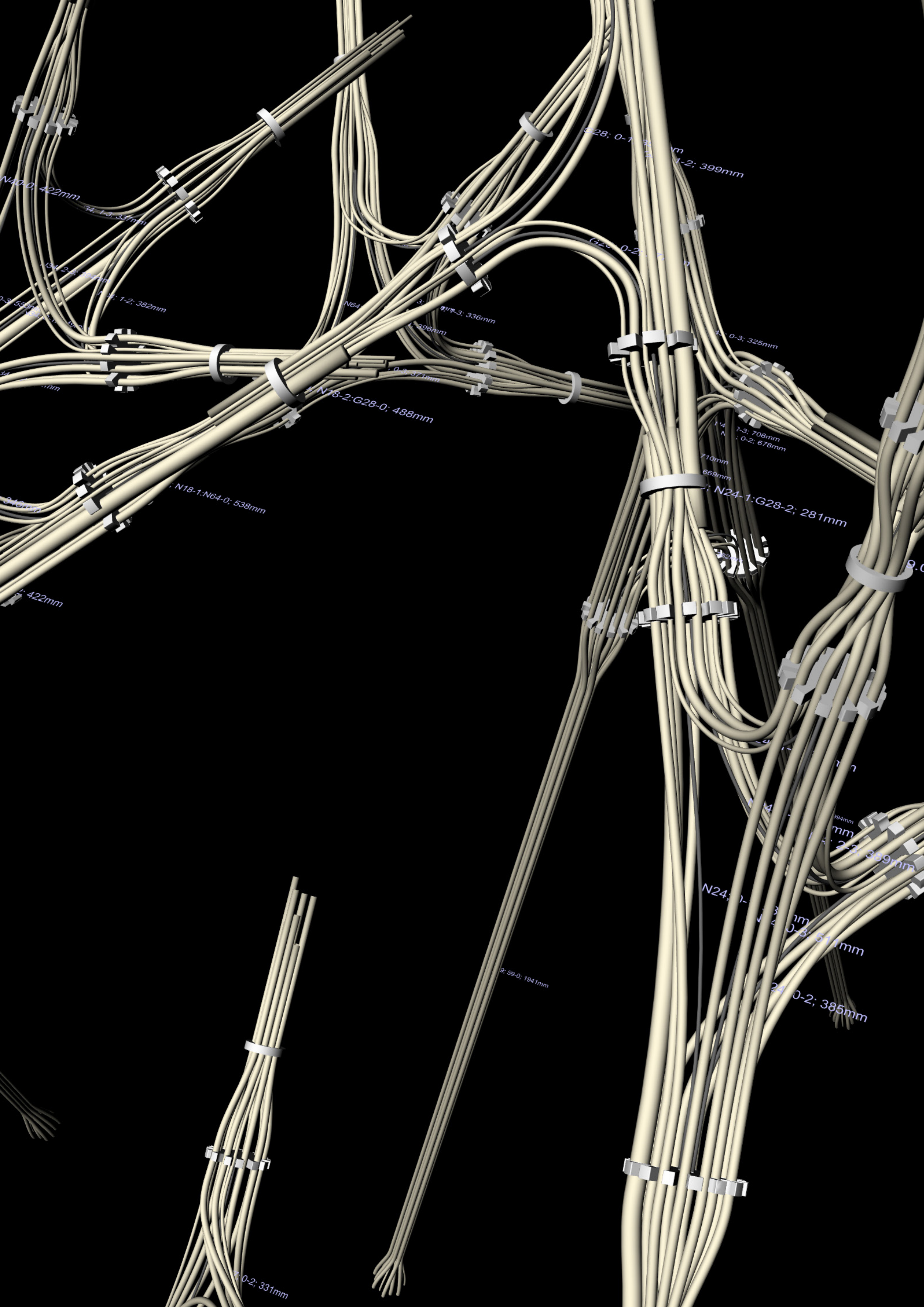
Part II: Publications



1-2; 399mm
N40-0; 422mm
1-2; 382mm
2-3; 336mm
396mm
0-3; 325mm
0-2; 371mm
N18-2:G28-0; 488mm
0-2; 678mm
N24-1:G28-2; 281mm
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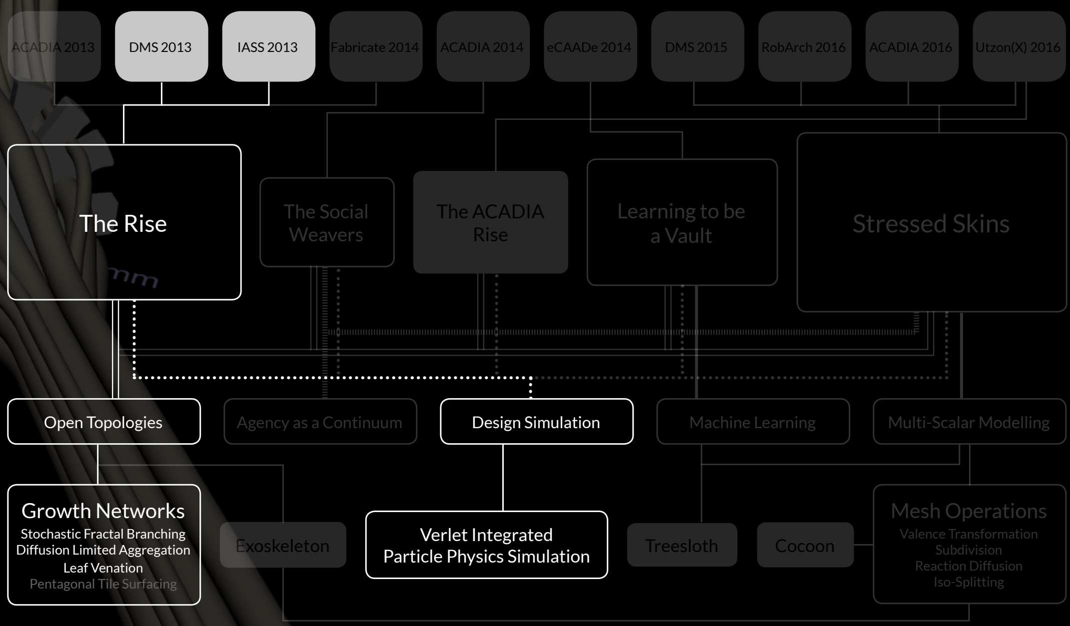
0-2; 331mm



Publications I: The Rise

The first and second publications are here presented for their examination and dissemination of the research experiment *The Rise*.

> Tamke, M., Stasiuk, D., & Thomsen, M. R. (2013). *ALIVE: Designing with Aggregate Behaviour in Self-Aware Systems*. In Proceedings of The Design Modelling Symposium 2013: Rethinking Prototyping, 257-275.
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> Tamke, M., Evers, H. L., & Stasiuk, D. (2013, September). *Growing Timber Structures–Growth algorithms as an alternative approach for integrating design with constraints from materiality, tectonics and production*. In Proceedings of IASS Annual Symposia (Vol. 2013, No. 14, pp. 1-10). International Association for Shell and Spatial Structures (IASS).

Engaging in Open Topologies and Design Simulation

Because *The Rise* was the first experiment undertaken in my research project, it most closely reflected the initial motivation that animated it. This aimed to problematise and in some manner unlock the fixed and explicitly authored boundary conditions that typically define the parameter spaces in computational design models. Although model formulation requires some establishment of boundary conditions by a designer or developer, models whose parameter spaces are more rigid lose their flexibility: when the number and connectivity of both parameters and algorithmically produced model elements are explicitly defined, models lose the potential to increase design intelligence and support processes of invention and discovery. And the more specified these boundary conditions are, the greater the design system will reflect a predetermination toward a model result. This "topological" rigidity in the setup and deployment of model parameters had been identified as an initial target of concern in model formulation, and a primarily research question became whether it was possible for models to self-parameterise.

As it pertains to this research project, the primary vehicles of inquiry that aimed to address the rigidity of parameter space definition in the modelling and development of *The Rise* were open topologies and design simulation. Here, it is hypothesised that more tightly integrated feedback loops between morphogenesis and the simulation of material behaviours activate more open-ended and increasingly adaptive design systems. The following papers detail how *The Rise* engages in these interests, both in its model formulation and instrumentation, and as it integrates its pursuit of other motivations, relative to its design brief as part of an exhibition engaged in biomimicry, and in the research interests of other investigators pursuing the deeper integration of material properties in design processes.

Collaboration

This last concern reflects an important additional focus for this research project, which considers effective collaboration as a central component to the implementation of successful design modelling approach. This is reflected in the methodological contribution toward practice that this project claims, whereby discrete modelling systems within experimental projects may also contribute holistically at the scale of practice, and where their integration is considered as a target of epistemological interest.

Key here is the assertion that design modelling systems should be developed to simultaneously support a range of interests – here in direct response to the overly rigid and inflexible nature of overly-specified parameter spaces – and as a result embody the flexibility to map to multiple applications. The second paper for *The Rise* is presented in this context: that the growth-based algorithms that were developed as design probes for its initial exploration were also extended to other projects for which I did not participate as a principal researcher, but to which the modelling systems I developed were directly applicable. In this case, the implementation of a leaf-venation algorithm developed as a design probe in early investigation of *The Rise* – and ultimately not used in that context – nonetheless became central to a different design project pursued within CITA, specifically for an asymmetrical timber canopy whose form was adapted to address goals for both daylighting and structural performance.

Project role

In addition to my being the exclusive developer of the modelling systems used throughout the project – including design probes, simulation systems, generative logics, and fabrication drivers – I also closely collaborated in the project's conceptual formulation, its design, the development and testing of physical prototypes, and installation.

Author role

My contribution to these publications is similarly broad. I authored the technical portions of each paper that focus on the modelling systems used throughout the design exploration, development and production of *The Rise*. Additionally, I contributed significant portions of the text that present and reflect on the theoretical frameworks concerning motivation, research questions, and findings.

Presentation

The papers presented here have been reformatted for continuity, but all textual and visual content remains unaltered from its original, peer-reviewed presentation.

4. ALIVE: Designing with Aggregate Behaviour in Self-Aware Systems

Reformatted from: Tamke, M., Stasiuk, D., & Thomsen, M. R. (2013). *ALIVE: Designing with Aggregate Behaviour in Self-Aware Systems*. In Proceedings of The Design Modelling Symposium 2013: Rethinking Prototyping, 257-275.

Abstract

Contemporary building design is increasingly engaging a practice where sensed or simulated data informs a computational design model. In order to use the iterative power of computation a parameter space is developed, in which a generative model is placed to find an appropriate design solution. Its performance and behaviour is then visualized through either a physical or simulated manifestation. Repeatedly cycling through this process of parameterization/generation/simulation/analysis enables the designer to optimize for selected effects and characteristics of the model. The problem of this approach lies with the execution of feedback. Parametric design tools are practical, but they effectively rely on the definition of base infrastructures that operate within a fixed set of boundary conditions. An inherent resistance to change in the modelling environment during the design process emerges as a result. Hence attempts to address the changing state of our environment and to find appropriate design solutions face the fundamental limits of the computational models that underlie contemporary practice. How can the

Figure 1: The research-based installation "The Rise", commissioned for the spring exhibition "ALIVE – Designing with Living Systems" at the EDF Foundation ESpace / Paris. Photo by Anders Ingvartsen

rigidity and overly-deterministic behaviour of our models be overcome, and feedback become an integral part of them? Is it possible to collapse this digital design cycle such that morphogenesis and the simulation of material behaviours operate as an interdependent whole? How might this modelling process engage in an iterative dialogue with physical material design and analytical approaches?

4.1 Introduction

Natural plant growth presents a diagrammatic framework for investigating these questions. Plant formation is accretive, and successive growth iterations depend on the physical properties of previously accumulated matter, in relation to both the plant itself and its environment. As a result, the physical manifestation of a plant reflects the interplay between an internal rule structure unique to each species and each plant's individual environment. The mechanisms that describe the motivators and geometric principles of plant morphogenesis are known as tropisms. In plants, the operating mechanism for differentiation during formation is auxin – a hormone that directs new cellular growth and coordinates the emergence of the plant's geometry. The local presence or absence of auxin throughout the plant triggers the distribution of those available resources required for growth.

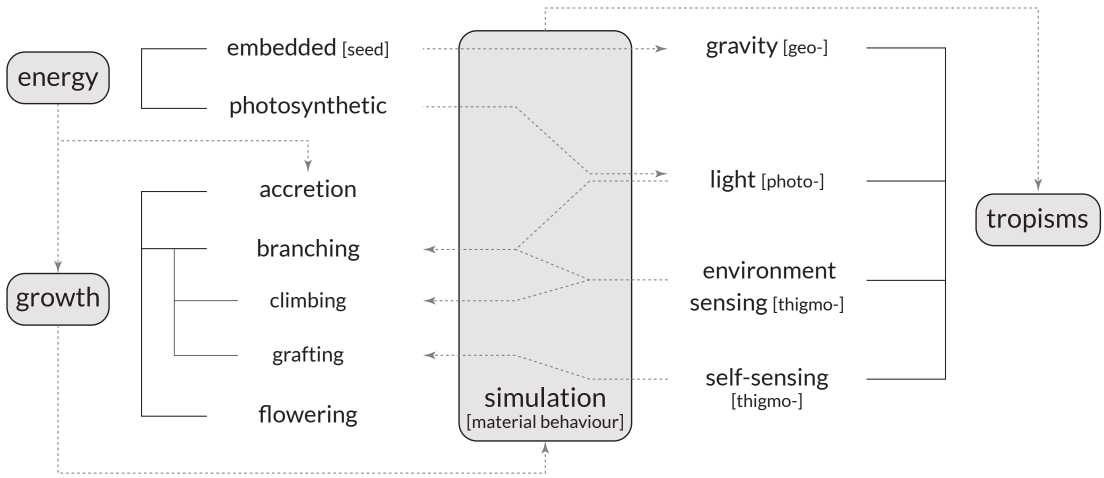
The research-based installation "The Rise" (Fig. 1) executes a diagrammatic transformation of these growth processes into a generative, simulation-based computational growth system. Crucially, this generative digital system is coupled with a process of materially-driven design and analysis techniques in the development of a multi-platform model. Through prototyping the generative digital model is refined through physical form finding and exploration and calibrated by empirical observations. Finally, these processes are deployed in a digital fabrication model that deploys construction information across all digital and analogue platforms necessary for installation. In this process multiple design tracks are executed in parallel with one another, with a strategic interplay between them re-informing and mutually amplifying the value derived from each track. This applies to idea formation, design development, material performance inquiry, prototype, and ultimately fabrication and assembly.

In order to facilitate the research focus on a material simulation-driven generative system as expressed in the scale of the installation (5m x 5m x 5m cube), it was desirable that the material chosen for the assembly should exhibit somewhat exaggerated behavioural characteristics. Rattan core was selected based on its high degrees of bending flexibility, resistance to breaking, and strength in tension. The solid rattan has a soft fibres structure that provides it with way higher flex than that of other massive wood from coniferous or deciduous trees or the hollow bamboo. However, all these materials are vegetal, slender, tapered and elastic and as Siegfried Gass stated in 1985 "…are subject to deformation, in particular in the case of bending loads, to a much greater extend the construction elements normally deployed..." In the same publication the authors described furthermore the fundamental techniques to use these slender poles in construction systems. Among these bundling, which enables larger loadbearing for poles in comparison to the pure addition of individual poles, and branching, as a mean to reduce the mass of a system and to enable an arrangement that follows the flow of forces (Fritz), where utilized in The Rise as a way to mimic the behaviours of cellular vegetative growth. Here the rattan core is used through a process of tight bundling along trunk and branch growth and multi-directional active bending collections at each branching moment. The rattan exhibits bending behaviours that facilitate both fabrication and calibration of the digital design system in its continuous simulation of material characteristics during morphogenesis. The model's dynamic topology is then directed to branch and multiply according to its internally encoded logics as a response to its environment and furthermore in direct response to its own behaviours in light of continuous accretion and material simulation. Through these logics the installation explores the use of highly redundant, distributed systems as an alternative to traditional structural systems.

4.2 Growth Processes

The biomimetic model for "The Rise" endeavours to collapse the standard design cycle – parameterization/generation/simulation/analysis – such that both material intelligence and environmental sensing are embedded in a continuous particle-based physics simulation, calibrated through measured, real-world material behaviour. The simulation is interdependent with incremental topological reactions in the model geometry. Performance and behavioural analyses are fully integral to this time-based sensing/growth/material simulation algorithm. This approach moves toward a modelling system that can become aware not only of the environment, but of its own reactions to external stimuli. The generative model for "The Rise" emulates tropisms (Esmon) during morphogenesis (Fig. 3). For our modelling process, we focused on three types of tropisms: phototropism (light-driven response), geotropism (gravity-driven response) and thigmotropism (touch-driven response). We interpret tropisms through the algorithmic deployment of directional orientation and task assignment during branching, self-grafting and climbing. Essential to this is the abstraction of tropisms from the type of cellular accretion that plant growth is actually comprised of to the emulation of its overriding morphological and purpose-oriented characteristics. So, phototropism operates as a means to inform both the new direction and branch type for new growth tips that emerge during branching moments. Based on their orientation toward both the primary light source and their physical environment, new branches are first assigned roles as either being light-seeking or structural, and then they are given their initial growth vector. This process can be observed in the model system described in Figure 5. Thigmotropism is exhibited in the model through growth tips sensing proximity either to the physical environment, which leads them to fix as climbers, or to other branches, which leads them to grafting. In all cases, the actual processes exhibited in

Opposite Page: **Figure 2**: Algorithmic interdependencies in the generative model for "The Rise": abstractions of energy, tropisms and growth responses are processed through a particle simulation system into a self-organizing assembly; and **Figure 3**: Diagrammatic transformation of natural tropisms into an algorithmic, digital morphogenetic system


energy
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tropisms

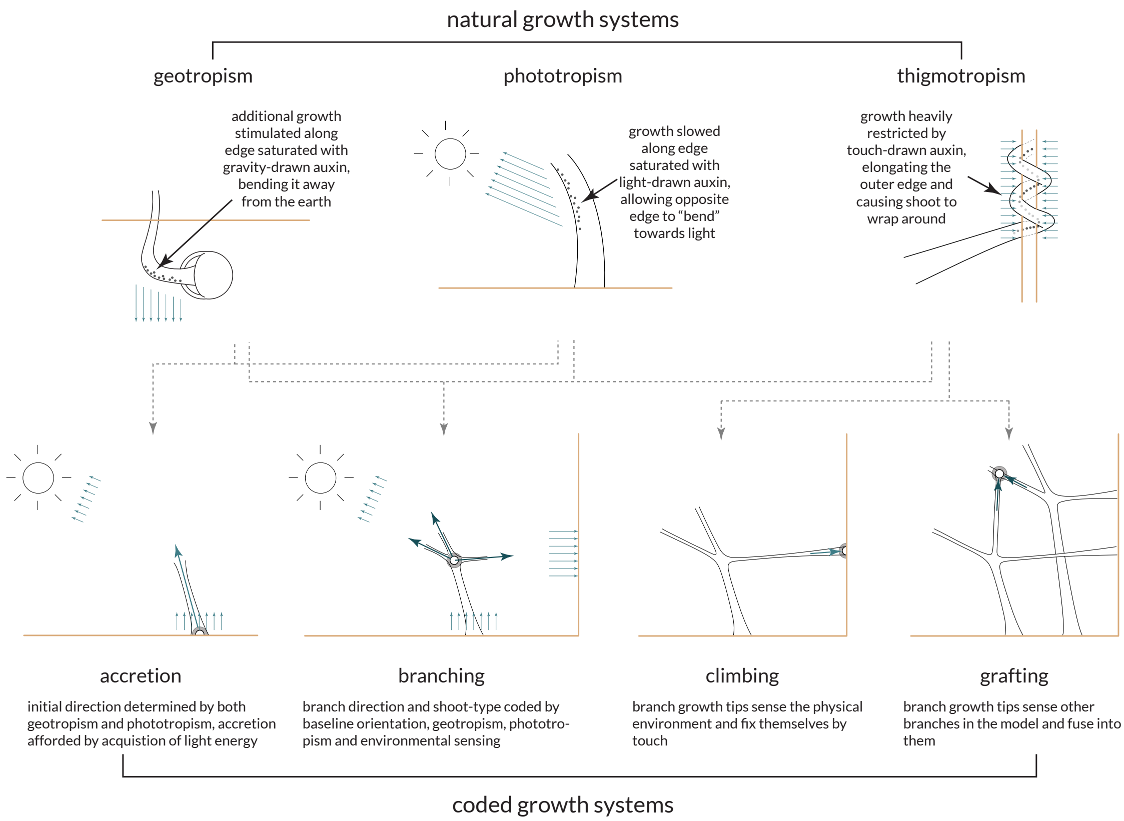
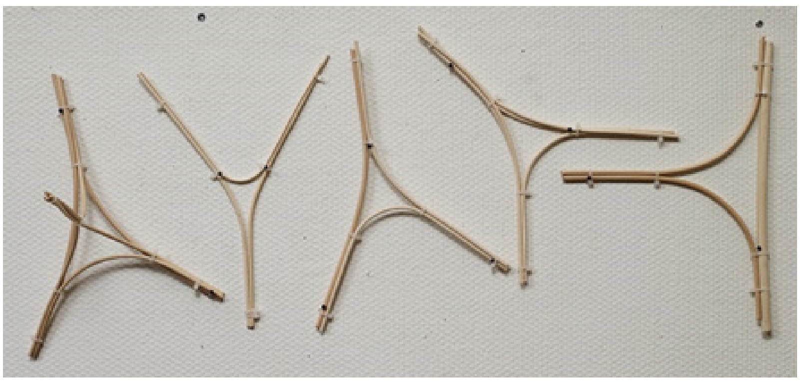

natural growth systems
geotropism
phototropism
thigmotropism
additional growth stimulated along edge saturated with gravity-drawn auxin, bending it away from the earth
growth slowed along edge saturated with light-drawn auxin, allowing opposite edge to "bend" towards light
growth heavily restricted by touch-drawn auxin, elongating the outer edge and causing shoot to wrap around
accretion
initial direction determined by both geotropism and phototropism, accretion afforded by acquistion of light energy
branching
branch direction and shoot-type coded by baseline orientation, geotropism, phototropism and environmental sensing
climbing
branch growth tips sense the physical environment and fix themselves by touch
grafting
branch growth tips sense other branches in the model and fuse into them
coded growth systems

Figure 4a: speculative physical model investigating tropisms, branching, grafting and flowering. Photo by Anders Ingvartsen

Figures 4b and 4c: early investigations of active bending in branch geometry



plant tropisms are simplified from highly complex, chemically-driven cellular-level processes to diagrammatic representations of growth intent.

In addition to this application of tropism-like characteristics, our model also relies on the diagrammatic simulation of light providing energy for growth activation. It utilizes a series of energy variables that are distributed according to each local branch's proximity to a light source: the closer to the light, the more energy is given for the distinct growth processes of lengthening, branching, climbing, self-grafting and flowering. Simultaneous to these simulations of tropisms and energy acquisition directing the accretion of new growth, resulting geometries are continuously activated by an on-going physics-based simulation of bending and twisting under self-weight (Fig. 2). This endows the growth model with the rattan material characteristics during its formation. As a result, the form is as much a non-deterministic material response to its own geometry as it is to the integral formation algorithms that dictate the properties of its modular accretion.

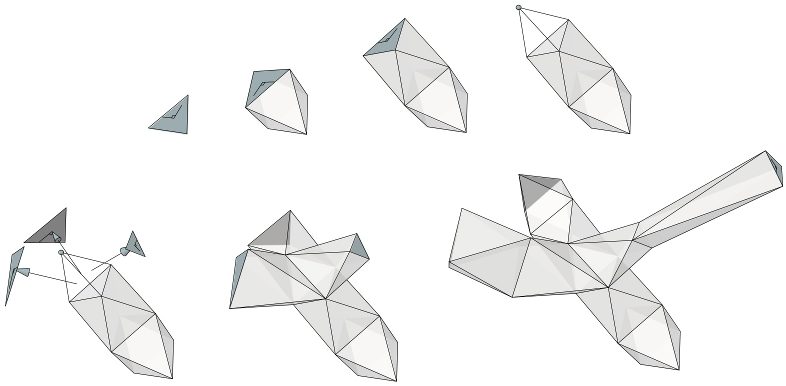
The parameter space that drives the algorithm for the digital model is developed in tandem with a series of material studies (Figs. 4a, 4b and 4c) that provide direct physical feedback for directing growth geometries, managing branching and grafting processes, and the registration of material behaviour. The early speculative models that explore global configurations are informed by the generative processes already established at the time of their creation and in turn perpetuate the design feedback loop by providing a formal and conceptual scaffold upon which to continue to re-develop, re-inform and re-calibrate the installation's digital parameter space.

4.3 Topology management, simulation and initial digital calibration

The use of a centralised geometry system for the navigation of multiple design priorities proves crucial for the installation model: careful management of model topology is instrumental not only to its continuous physical simulation, but for all other aspects of the recursive growth algorithm, and for later use in the production of detailing and fabrication models. Importantly, it also provides a clear means for integrating observations of physical experiments performed outside the digital environment.

To achieve these goals, the model exhibits its growth through the accretion of minimal triangulated truss-like modules which are managed in a mesh (Fig. 5)

Figure 5: Minimally triangulated modular accretion and branching logics for management of spring-based system and growth/branching topologies



whose point, edge and face topology is registered and deployed in a custom-written particle-based spring and gravity simulation system for the exhibition of bending and torsional rotation during growth. (Figs. 6a and 6b)

Several investigations have been made into deploying alternative modelling approaches for the bundled assembly system. First of all, a more simplified polyline driven particle system for capturing the bending behaviour of each growth element has been tested. However, at moments of branching, the types of torsion that are observed in the physical material assemblies become difficult to manage with such an approach, as the bending forces applied in the particle system don't account for orientation, only the desired angle of bending between particles. Although the development of a force to account for maintaining branch orienting is explored, it ultimately exhibits limitations both in the form of instability during simulation and in terms of reducing more cohesive and realistic overall behaviours. Based on this experience and challenges met in further research into a means to define a specific force for a given particle's orientation around a primary axis (a normal defined by the member direction at a given particle), the simplified triangulated truss is introduced. By modelling the bundled system in such a way, both the bending and torsional behaviours as observed in the physical prototypes are approximated, and in fact bending forces are altogether eliminated in favour of collections of springs embedded in these accumulated tubular elements. The parameterisation of spring stiffness, particle mass, strength of gravity, and the radius and length of each growth module is informed through empirical observations of both the digital and physical, and a feedback loop is initiated between the both of these environments for the purposes of calibrating the overall system. (Figs. 7, 8a, 8b and 8c)

The execution of the generative algorithm as informed by the observed material behaviours and managed through the topological system outlined above results in a model that captures the active bending behaviour of bundled rattan, incrementally grown into place under continuous transformations resulting from the simulation of self-weight. Ultimately, based on the intentions and constraints of this project, questions regarding specific material descriptors and structural performances – such as flexural modulus and longitudinal stiffness – are disregarded in favour of modelling for direct adherence to empirical observations based on the testing of prototype performances and behaviours. This reflects a significant opportunity for future development of

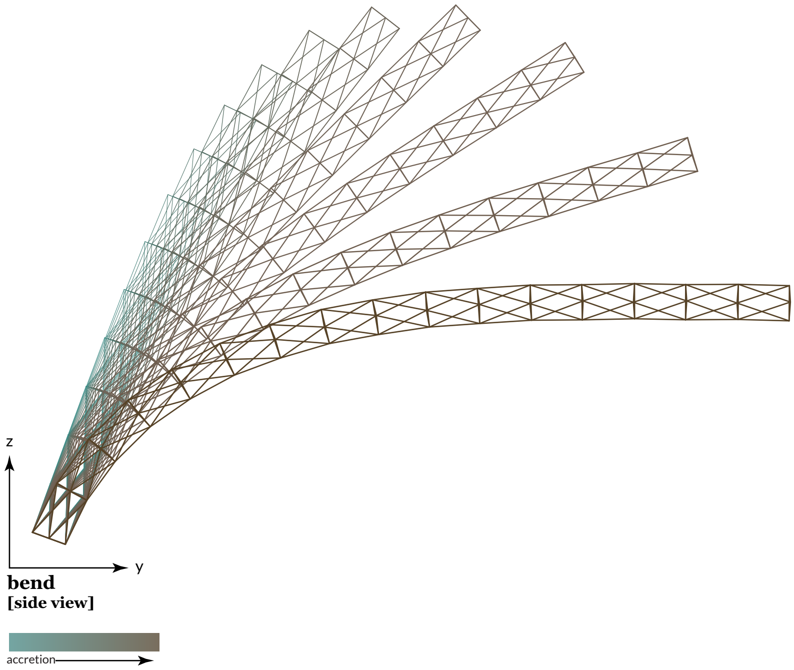


Figure 6a: Bending under self-weight as a function of growth over time, captured as a gradient from white to red

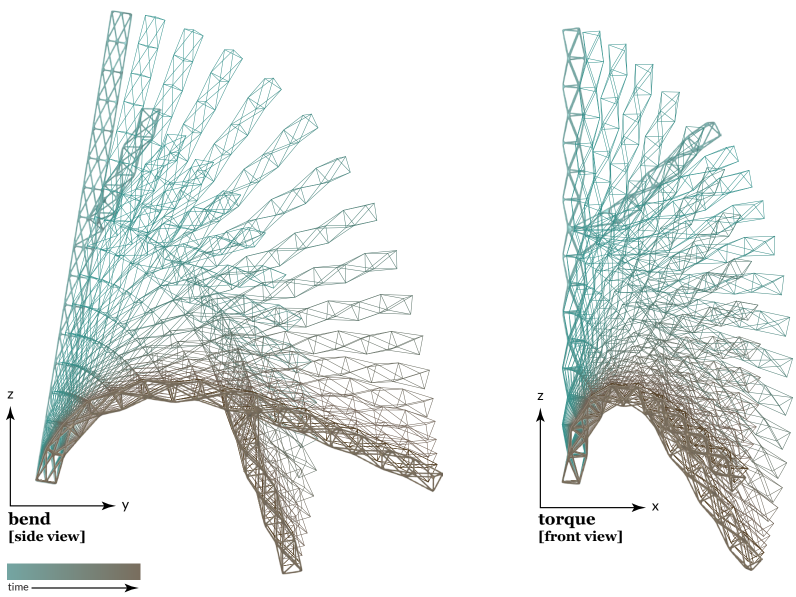
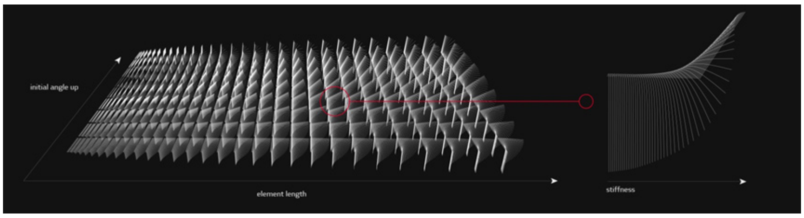


Figure 6b: Bending and torsional rotation behaviours embedded in simulation

Figure 7: Analysis of bending behavior in particle system examining initial growth angle, final length, and spring stiffness



(Clockwise from left) **Figure 8a**: analysis of bending and creep by section and variable loading conditions; **Figure 8b**: early bending test of rattan bundle; **Figure 8c**: identification of minimum bending radius by rattan section. (Hollie Gibbons)

such a system, that it seeks to more carefully integrate and track these material and structural measurements.

Additionally, the measurement of each spring's deformation as it reacts to further module accretion generates data regarding both tension and compression (Figs. 9a and 9b) that proves crucial to the sizing and distribution of rattan members during detailing and fabrication.

The assembly logic used for fabrication is expressed as a series of struts and connection nodes. Each strut is comprised of a tightly packed bundle of variably-sized rattan elements that behave as primary structural members and tie related connection nodes together. Each connection node is formed using the active bending (Lienhard) properties of its composite rattan members such that desired geometric outcomes are achieved through opposing bending resistance by the members in each node. This integrated detailing system emerges through a similar engagement between a series of physical and digital design iterations and calibration processes. (Figs. 10a and 10b)

Because the primary generative model relies heavily on simulation to achieve its results, complexity in its topological setup is necessarily minimized in order to maximize the complexity of its emergent behaviours. In contrast, the assembly system demands a high degree of complexity in its topological organization.

For this reason, the digital model is split into two sequentially executed states, one for generation, and a second for fabrication. The fabrication model is also parametrically driven and is entirely dependent on the generative model for geometric configurations and critical information related to overall topological relationships between branches and the distribution of material for structural

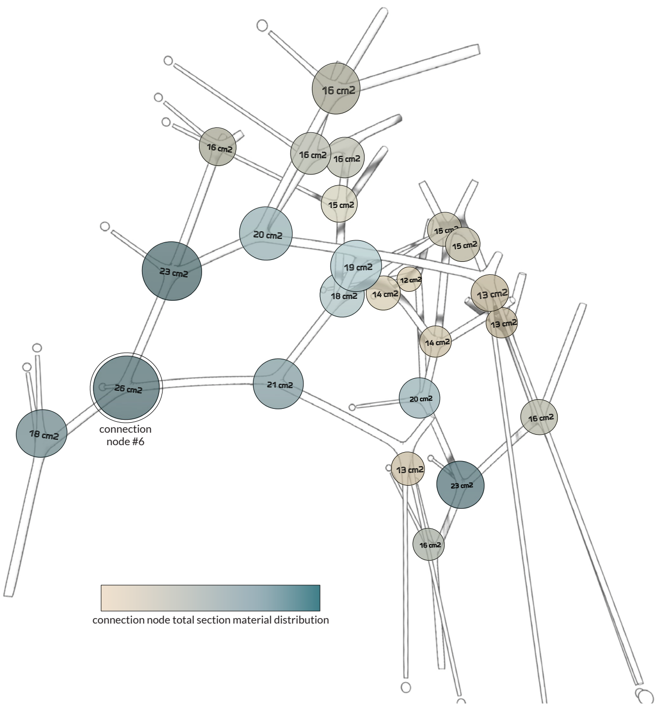
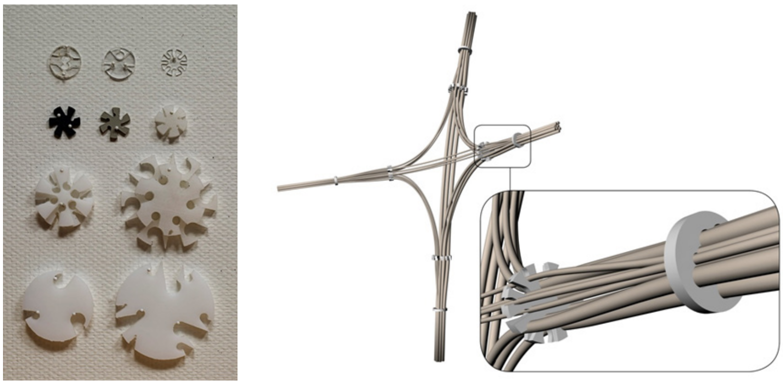


Figure 9a: Overall generation with registration of spring deformations derived during morphogenesis

Figure 9b: Distribution of material thicknesses along each connection moment (and subsequently along each bundled strut) according to total spring deformation

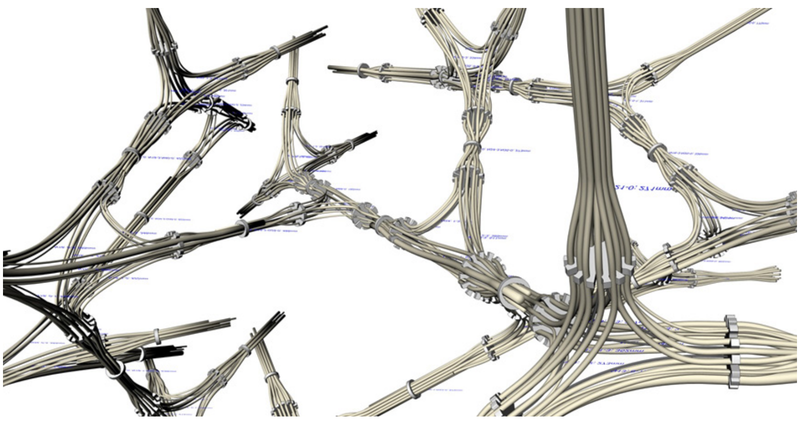
Figure 10a: explorations of star system; **Figure 10b**: development of 3d digital array for integrated packing-node/star connection system



performance. It converts these data into the digital fabrication files that drive the CNC milling of over 500 bespoke HDPE connection components, and the information for the sizing, arrangement and enumeration of over 500 individual rattan members. It also supports fabrication sequencing. Because it is a fully developed digital model (Fig. 11), it provides a final opportunity for further analysis and re-calibration through a comparative analysis of the idealized 3D model with a 3D scan of the final installation (Fig. 12).

In the addition to the key role active bending simulation plays in model morphogenesis and global structural performance, it also is the primary means by which each individual node expresses geometric variation. The material's systematized elastic deformation is then an integral part of the system's architecture (Lienhard) and is critical to the creation of branching points and calculations of member sizing and distribution. Embedded information about the material's minimum allowable radius and bending behaviours – identified and analysed during the prototyping and development phases – couples with orientation and deformation information provided by the simulation to dynamically size members at each node and along each strut. For any four-point node topology, there are a total of six possible connection pairs. Also, for each node, the total material sectional area is dictated by the amount of global deformation the node is required to resist, as anticipated through the

Figure 11: Generated detailed model showing bespoke variation of material thicknesses in nodes and struts, star and packing node distribution system, numbering processes and dynamic continuity of fibres throughout the model



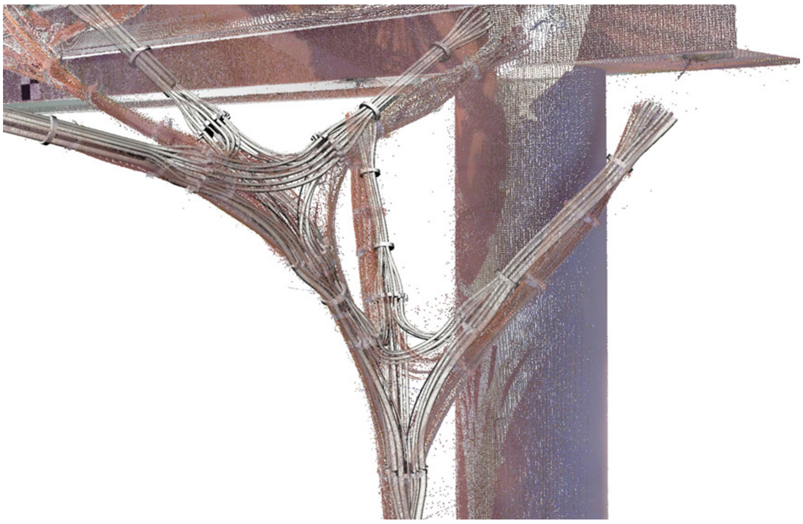


Figure 12: Generated detailed model overlaid with 3D scan of built installation (Martin Tamke)

Strut connections between nodes are designed to maximize the continuity of single rattan members. After each connection has been configured, a comparative an analysis is performed between stars that share a strut. The section of each member for each star is mapped to an average plane between connecting stars. Member of identical size from adjacent starts that falls within a set radius of each other on this plane are fused into a continuous member. All remaining members are set to overlap with terminating members from the other node within the strut and cut (Figs. 15 and 16). Finally, a loose packing simulation using the Grasshopper plug-in Kangaroo is performed to bundle the rattan along the struts and reinforce their active bending performance. The profiles of these packed members are captured and deployed during fabrication.

4.4 Discussion

"The Rise" demonstrates the potential for using algorithmic growth-based design processes for the development of working structural systems in a changing environment. It achieves this by collapsing the space between generation, simulation, analysis and feedback and reducing the distinction between each to a brief moment of internalized computation. Through this, morphogenesis is accomplished in a system able to directly couple generative strategies with material behaviour and consequence, such that iterative stages of accretion and organization directly rely on previously accumulated geometry and resulting simulated performance characteristics. The performance is here directed through feedback loops that parse internal behaviours calculated through physical simulation and the sensing of external factors, such as the possibility for a branch to gain strength through joining with its neighbour.

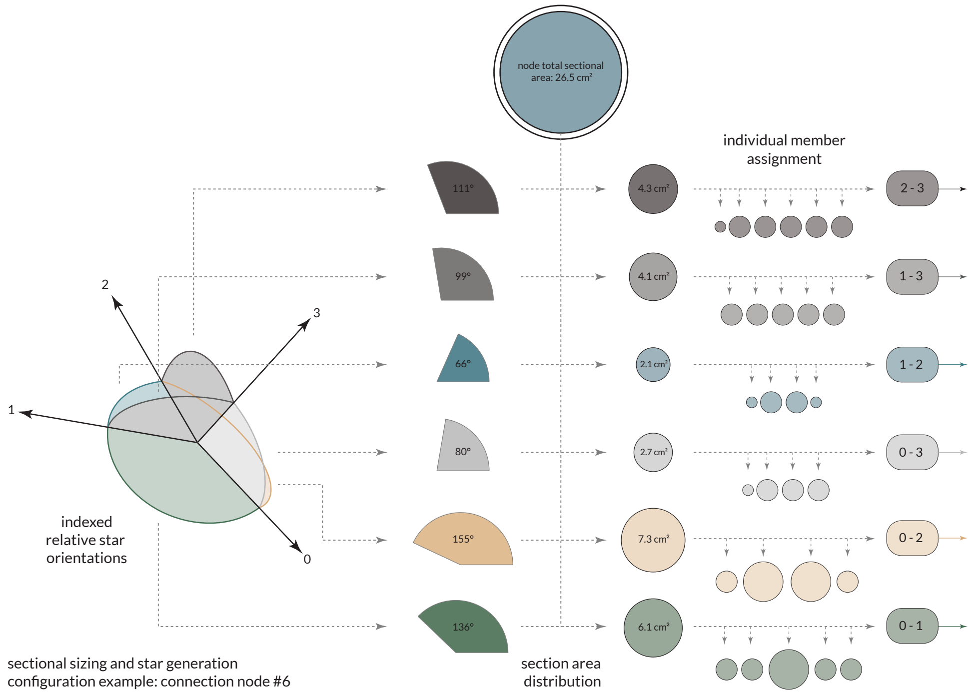
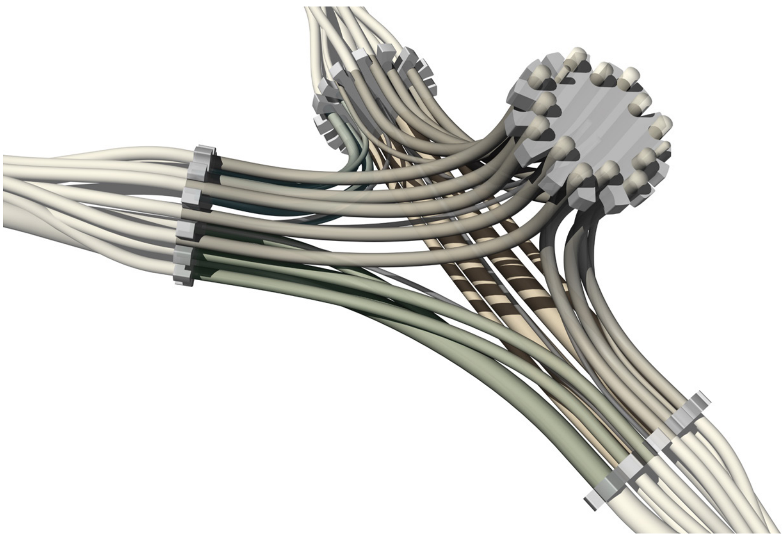


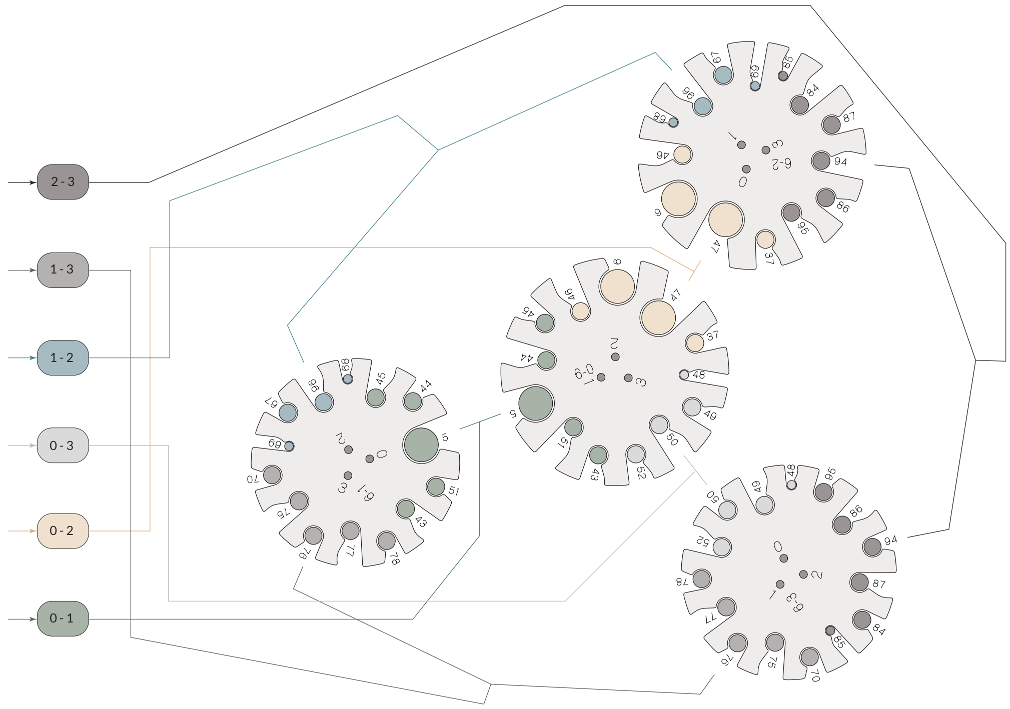
Figure 13: (This page and opposite) Example of node sectional material distribution scheme and star configuration array (for node #6)

Key to this approach is the understanding that the environment of a design system is comprised of both extrinsic and intrinsic factors (Simon 1969) and that each must inform the algorithmic decision-making process. As responsibility for local decisions becomes embedded within the system's response algorithm, the process of design shifts such that the designer's role is situated within the system's parameter space (Tamke 2011).

"The Rise" showcases the implementation of a design´s internal history: earlier

Figure 14a: Digital Representation of node #6





design decisions, such as those in "The Rise" that trigger growth, branching, joining or climbing (Fig. 17), have an inherent influence on the current state and the potential space for new decisions to be made. Where actions from the past cannot be undone The Rise shows how the often purely forward oriented decision-making process of generative systems can be overcome. Evolutionary algorithms identify break points for starting a new iteration in pursuit of a global optimization (Derix). "The Rise" follows another avenue: like a

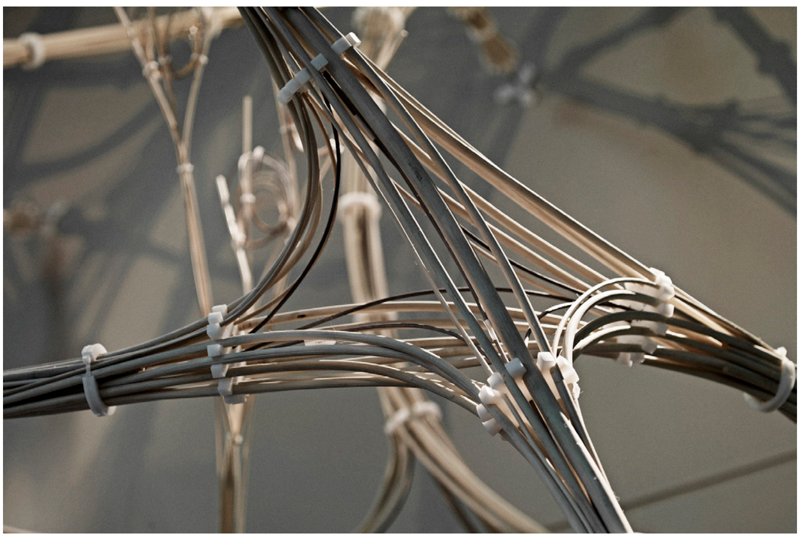


Figure 14b: node #17 in situ. Photo by Anders Ingvartsen

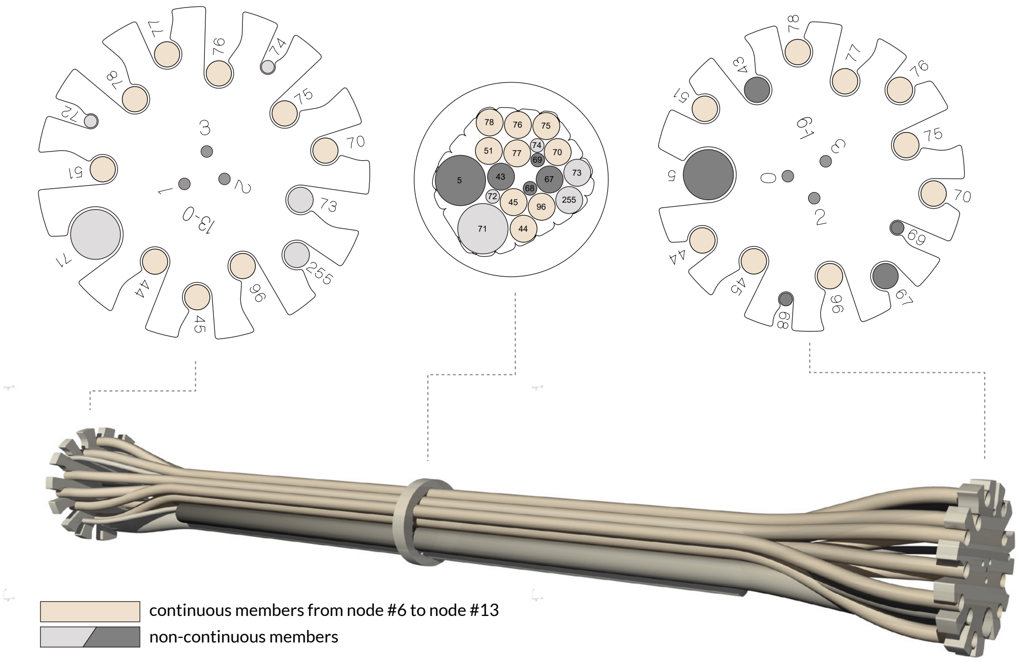


Figure 15: Digital representation of strut topology for connection between node #6 to node #13, exhibiting member continuity and solved packing node.

vegetative system it has the ability to readdress previously generated elements and change them. In order to do so the Rise operates on a differentiated set of scales: as it is aware of its overall state it is able to change such non-topological parameters as the strength of established struts recursively, while topological decisions remain untouched; conversely it also has the capability of transforming topology in pursuit of its goal.

A sense of consequence emerges and introduces a time-based logic that goes beyond the never-ending sequence of real-time computational looping. The question of the time-scape of architecture and the space of its actions

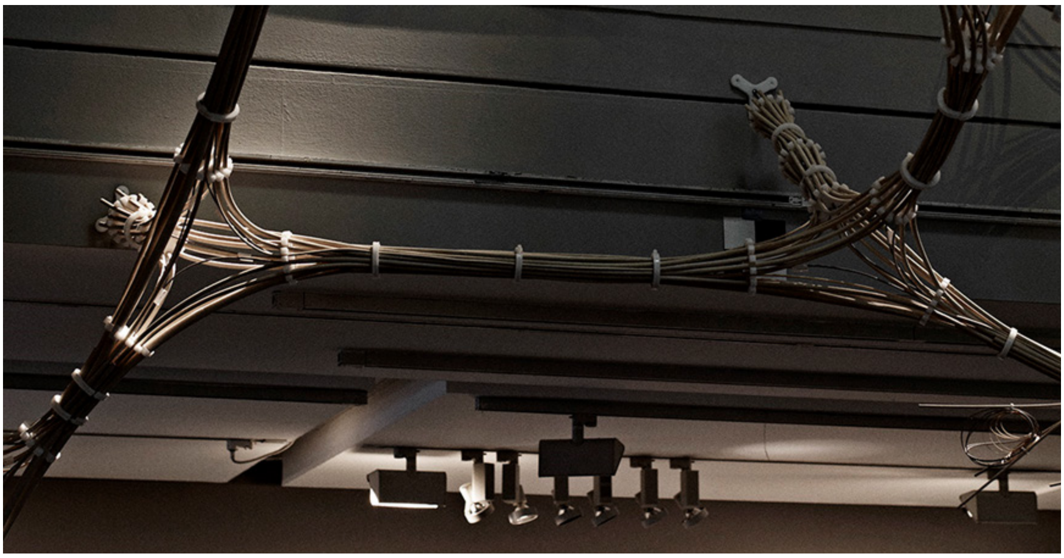


Figure 16: Strut connection between node #6 and node #13. Photo by Anders Ingvartsen

emerges. When “The Rise” occupies a generative space similar to that of a vegetative system and its underlying logic of growth, shouldn’t it operate in a similar timeframe – untouched by the flickering that occurs in reaction to every moment? And where this insight hints at the scale of time in which the operations of buildings have to be considered, how does a building process itself take on fundamental decisions about accretion and transformation? Are these decisions then leading to constant changes based on accumulated and evaluated knowledge about its timely behaviour?

“The Rise” operates in parallel between the physical world and the digital realm of the design space. Its Parisian manifestation is single expression in a long conversation about the development process of a material system that manifests itself through a collapsed simulation space. And although the physical realm provides valuable feedback, the digital design space remains crucial. It is here where the behavioural knowledge is accumulated and encoded in order to finally serve as basis for decisions about the initial parameter space. “The Rise” is hence based on a process of learning. This is not an automated process but has to be understood integral within the design process, the team and collaborators. It is essential that strategies for learning remain integral to the informed generative model design in order to not only leverage the ability to strategically manage the underlying codebase in order to train the system’s reaction and behaviour, but also to rethink the goals and boundaries of the physical artefact.

The coupled, parallel development of a generative tool with its material system creates for new strategies for design modelling, and as a result the

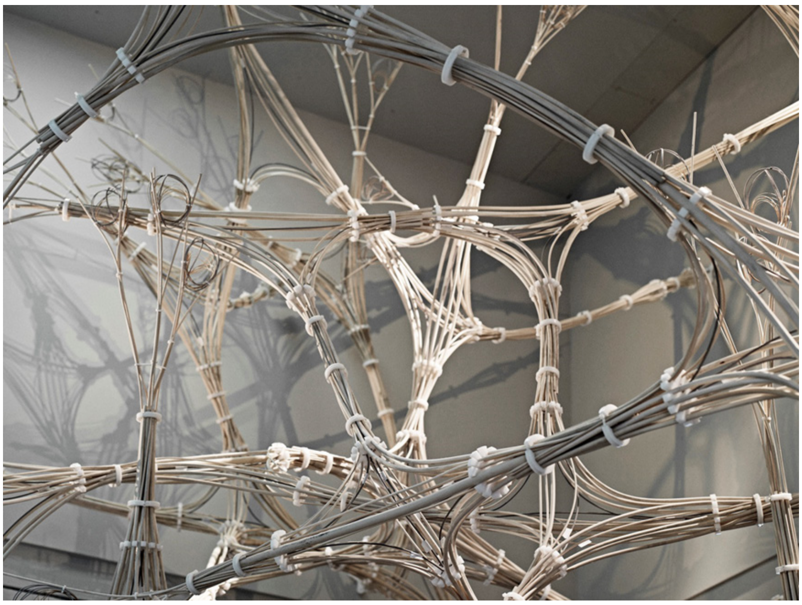


Figure 17: Detail of grafting and fusion of branches, that create loops and structural interconnection

design process becomes a process of learning. The calibration of the system's components allows for the integration of simulated complex behaviour in a lightweight generative design environment. However, the calibration process does not necessarily stop at the scale of the prototype. Further research into strategies of how self-parameterisation might be employed to in the modelling space may be conducted through a dynamic feedback analysis of the physical demonstrator in Paris as captured through high resolution 3d scanning techniques.

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5. Growing Timber Structures – Growth algorithms as an alternative approach for integrating design with constraints from materiality, tectonics and production

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Summary

The contemporary design of timber structures has to answer questions concerning structural stability, production impact and energy implications in ever earlier stages. The interrelation of these levels creates a complexity that is difficult to resolve through contemporary linear parametric computational models. Hence the lack of feedback about the impact of a design decision onto the design has been identified as source of problems. This paper reports on two speculative projects that integrate generative processes, based on natural growth patterns, with feedback from simulation in order to integrate the behaviour of networked systems into structures made from wooden material.

5.1 Introduction

Computational approaches [1] are the basis for design, planning and fabrication of wooden structures. In computational design modelling it is normal to iterate through a process of developing a parameter space, executing a generative algorithm based on this framework, and then passing the resulting model space through a simulation for analysis of performance and behaviour. As the results can feed back into the parameter space, designers are able to deploy a variety of strategies – such as evolutionary algorithms – to systematically re-adjust the parameter space. Repeatedly cycling through this process of parameterization / generation / simulation / analysis enables the designer to optimize the design for concerns regarding loads, the detailing of connections, and overall energetic behaviour or spatial ambitions. As robust as this methodology is, it nonetheless generally discretizes these operations and therefore relies on moments of both topological and parametric fixity: the simulation must be set, completed and analysed in order to re-inform the parameters and generative algorithms.

This notion leads in practice to a process that is restricted to a limited set of iterations, due to constraints in time and finances or the simple fact that the designers operating the different tools are prone to fatigue over the stretch of a project. The resulting iteration set fails to contain the exchange necessary to find a solution for the contradicting requirements that characterize the space of design.

Yet it is exactly this exchange that is to essential to the success of the building profession in an environment where more sustainable solutions are required in less time with more precision. The use of generative strategies for design [2] is here a means to increase the efficiency of iterative processing by simultaneously streamlining and making more robust the model operator's workflow. Structural systems with their logical setup and often clear hierarchy are especially appropriate for generative strategies. Where the generation of data can hence be automated the question remains how its analysis and generation can be linked in a meaningful way.

As such, it is essential to problematize the role of feedback in design and investigate means to address the rigidity and risks of those overly-deterministic model behaviours that can result from the separation of each of these crucial steps in computational modelling.

The separation of steps in the design of timber structures is especially problematic, as such systems are already tightly constrained by the material's anisotropic properties as well as the complex structural situations inherent in connection points [3]. The question becomes: what models allow for the constant reciprocal feedback between the different areas at play in generative design?

5.2 Coding natural growth patterns

Natural plant growth demonstrates effective strategies to integrate means of feedback with mechanisms for generation. Here tropisms – such as those reacting to light (phototropism) (fig. 1), gravity (geotropism) or touch (thigmotropism) – trigger auxin – a hormone that directs new cellular growth and coordinates the emergence of the plant's shape. Recent research in biology [4] led to the understanding of these processes on a computational level. Here an iterative process is described where after each step the current situation is analysed and further actions are decided. Here analysis and (design) action are inseparably integrated. Can a diagram of growth exhibited by living vegetative systems inform computational models in the creation of a self-propagating structure?

Figure 2.1: Phototropism in nature. (Martin Tamke)

Through a series of investigations into growth systems, we become interested in the idea of branching. There are many diagrams for branching logics, among which are included l-systems (both deterministic and stochastic), diffusion-limited aggregation (Fig. 2.2), and viscous fingering. These branching techniques tend to result in open branch networks, such that any one terminus will have a single path to the root of growth.

Because of our strong interest in developing systems that will operate structurally, we imagine multiple triangulations and therefore begin to focus on branching techniques that have the potential for generating closed networks. One such system we examine is that of leaf venation patterning, and we apply a generative algorithm to simulate it based on the modelling methodology described by Runions et al. This system depends on the interpretation of morphogenesis put forth by Pavel Dimitrov and Steven Zucker from Yale

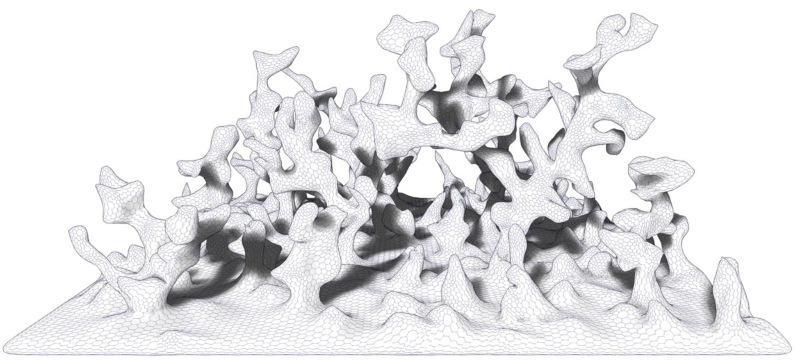


Figure 2.2: DLA growth on a mesh (CITA)

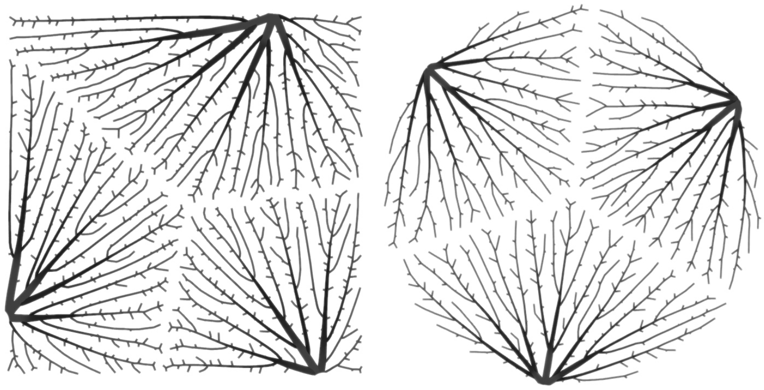


Figure 2.3: Open 2D venation growth diagrams with multiple sources (CITA)

University [5], whereby the hormone auxin, randomly distributed over the leaf surface, is transported along paths of least resistance in the canalization of new vein structures, whose directionality and splitting are determined according to each vein source's proximity to each auxin and the available growth space (Fig. 2.3). Topologically, this operates as a 2D system.

This process is then projected into a 3D implementation of the algorithm that allows for the formation of closed venation networks based on an analysis of proximity between both growing veins and each other as well as between the veins and auxin (Fig. 3). In the process of extending this approach to a closed, 3D system, a number of constraints associated with such a move become clear. In the first place, the research questions and architectural briefs in which both projects engage demand alternative spatial results and modelling performances not afforded by this implementation.

However, further iteration of the open 2D venation growth algorithm does lend itself to alternative forms of 3D projections in the form of multiply oriented and recombinant 2D planar spaces. Such assemblies become consistent with both the space-making goals of the project as well as with the desire for tightly integrated performance analysis in both natural lighting and structural behaviours. This further implementation will be discussed as

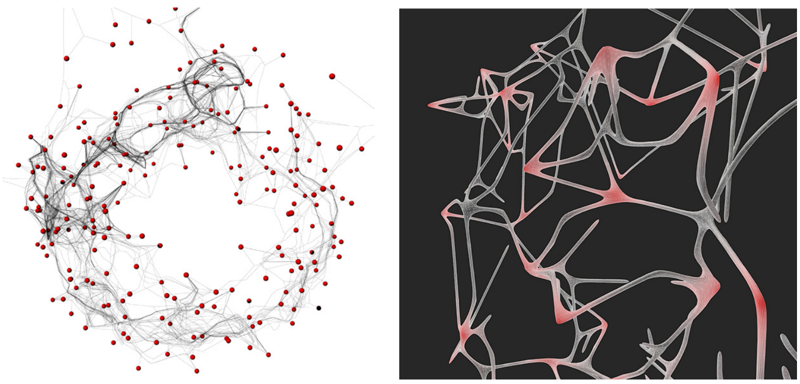


Figure 2.4: Closed growth systems based on leaf venation strategies, projected into 3D topological space (CITA)

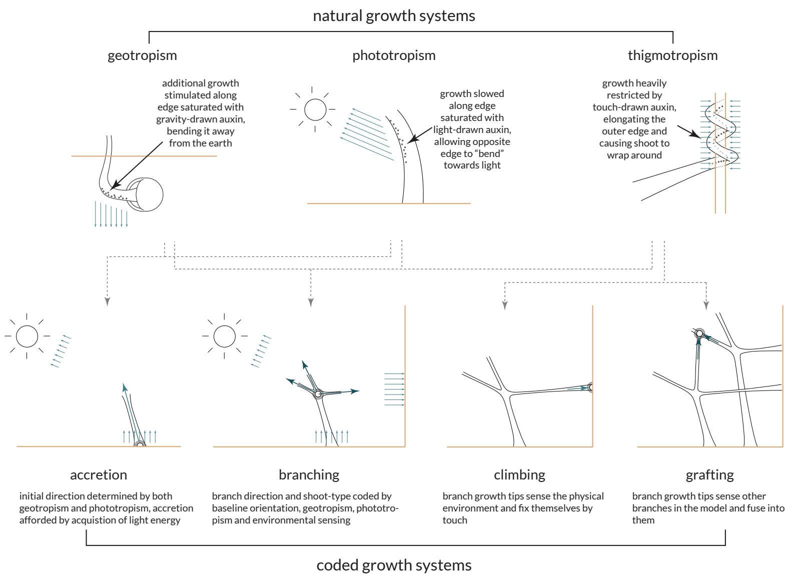


Figure 2.5: Diagrammatic interpretation of auxin-driven tropisms in vegetative growth for "The Rise".

part of the first project presented in this paper: a research collaboration with Krydsrum Architects in Copenhagen on the implementation of digital design and fabrication processes in a medium scaled architectural practice.

On a separate design track, the conceptual framework associated with the use of auxin proves crucial to the growth system deployed for the second project presented here: an installation for the EDF Foundation in Paris. In "The Rise" the hormone Auxin has, through the "fractal echo" [5] exhibited in plants', takes multiple roles. The mechanisms that describe the motivators and geometric principles of plant morphogenesis are known as tropisms, and auxin is here again the operating mechanism for cellular differentiation during formation. Examples of tropisms include those reacting to light inputs, gravity, electrical, chemical or hydrological environments, or touch. Within the plant's metabolism the presence or absence of auxin triggers local distributions of those available resources required for directionally varied growth.

The generative model for "The Rise" emulates tropisms during morphogenesis. For our modelling process, we focus on three types of tropisms: phototropism

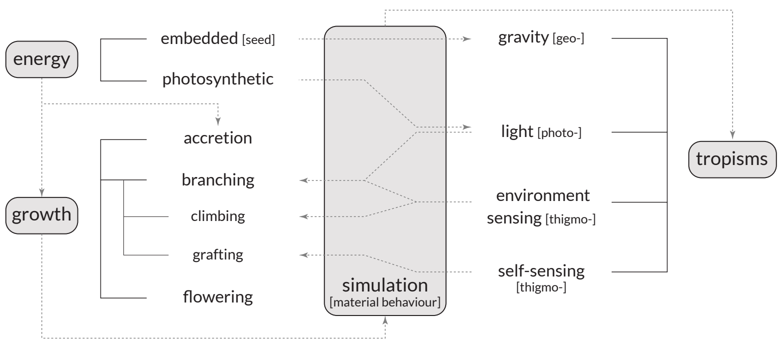


Figure 2.6: Synthetic sensing and simulation model for directional growth in "The Rise"

(light-driven response), geotropism (gravity-driven response) and thigmotropism (touch-driven response). In our model we interpret tropisms through the algorithmic deployment of directional orientation and task assignment during branching and those further topological transformations introduced in the form of the self-grafting and climbing (Fig 4.)

This diagram for directional cellular accretion becomes central to both the conceptual and modelling framework for "The Rise". In addition to engaging with biomimetic systems interpretation, accretive growth provides a means for investigating the possibility of collapsing the design cycle such that material intelligence is embedded directly in a continuously-running simulation of self-assessment, environmental sensing, and response to its own physical behaviour. Each growth step for the model is registered as part of an active and interdependent simulation system that synthesizes the interplays between energy acquisition and metabolism, algorithmic growth tropisms, environmental sensing, and physical response (Fig. 5). The resulting model topology is then unfixed for each growth step, and the parameter space can be seen as both dynamic and adaptive during morphogenesis.

A highly aware model emerges when decisions are taken based on the information it has about its state in the current spatial and temporal situation. Here analysis and (design) action are inseparably integrated. Can such a diagram of growth originally only exhibited by living vegetative systems inform the creation of a wooden self-propagating structure?

5.3 Wooden canopy – applying venation algorithms

The first project to explore these questions is a wooden canopy balanced on tilted wooden columns (Fig 3.1). The challenge here is to find a balance between the need to generate a self-carrying wooden roof structure that can at the same time provide on an overall level the shading necessary to fulfil

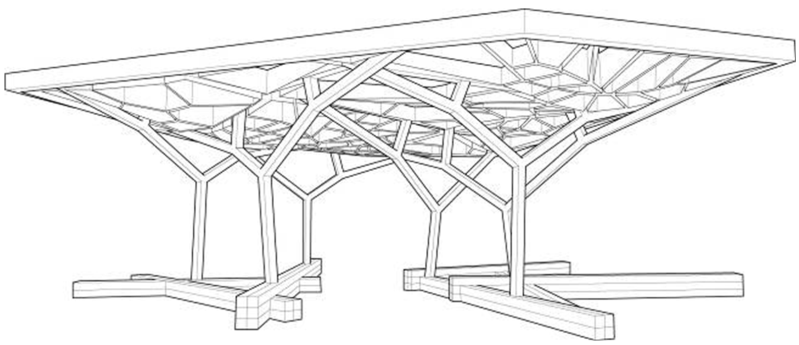


Figure 3.1: Drawing of Wooden Canopy. (Henrik Evers)

energetic concerns at different points of the day. These two requirements are interlinked with the positioning of load carrying branching timber columns. The venation algorithms guide the growth of the structure and are informed by an integrated FEA simulation that allows for the consideration of the structural as well as the energetic performances within the generative process.

5.3.1 Concept and outset

The outset for the study is the task – through the design of a wooden canopy – to negotiate between the constraints of the timber construction trade and the potentialities embedded in digital fabrication technologies. A multi objective generative design approach based on a single growth algorithm that is employed in different areas of the system is the point of departure. This algorithm can be tailored to different aspects of material, construction and behavioural properties.

Where Goethe's science describes natural systems as a constant interchange where the single organism is a pluralism of conjoined elements in continuous interaction with its surroundings [6], this study starts by separating the system into two different levels for the purpose of developing and testing a growth algorithm based on the previously mentioned leaf venation algorithm. This is tailored so that it can deal with two parallel objectives for the design:

- A stable timber structure utilizing digital fabrication
- The creation of distinct light situations.

As it is assumed that structural stability is the result of an internal negotiation and can be achieved within changing external condition, the stated light and energy requirements are instead externally imposed. Hence these two levels are addressed differently; the structural case with a post-growth analysis and optimization and the energetic case with a pre-growth analysis and condition

Figure 3.2: Automated timber construction industry. (Martin Tamke)

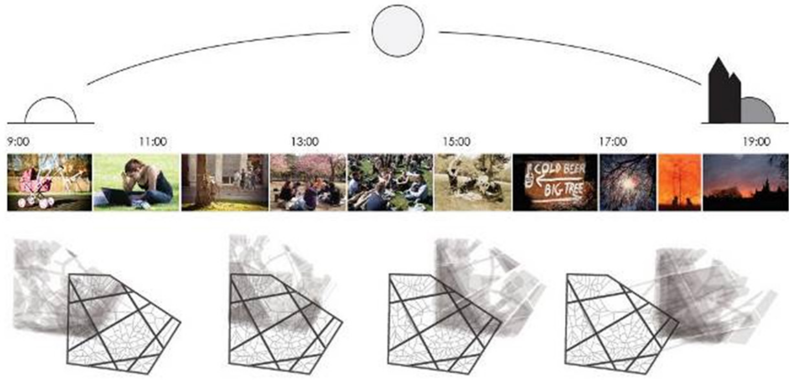


Figure 3.3: Illustration of shadow cast throughout span of day. (Henrik Evers)

setup. Both are however based on the same venation algorithm. The project becomes a study to test procedures and possibilities to adapt and eventually recombine generative algorithms in order to handle real world design and fabrication demands.

5.3.2 Aim and constraints for the algorithm and design system

The guiding design idea for the canopy was that of an asymmetrical canopy which is balancing on tilted columns mounted to interlocked ground beams. The canopy is made from loadbearing beams with a revolving edge beam. All load bearing parts are joined with steel plates. The areas between the canopy beams are filled with cassettes made of vertical portioned, thinner timber planks which are cut to a specific profile. Where these cassettes with their varying height negotiate solar energy and porosity, the placement of the columns is based on the changing boundary conditions from the canopy and ground.

The aim for embedding timber-related logics is to inform the generative processes with material and construction constraints. These are determined through a study of traditional and contemporary wood construction and manufacturing industry. The limitations of wood cutting machinery, jointing and planarity of assembly can be introduced as limiting geometrical conditions within the tailored leaf venation algorithms. The introduction of construction related limits is introduced in a similar manner to the tailored venation algorithm.

Figure 3.4: Solar study sets seed and auxin accordingly to desired shading. (Henrik Evers)

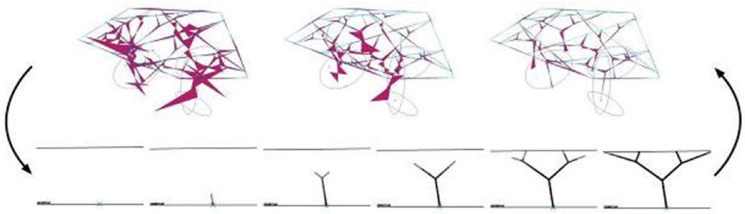


Figure 3.5: Growth of column in an iterative process of growth, FEA simulation and evolutionary optimization. (Henrik Evers)

The ambition for integrating light-based performances is to control levels of daylight at specific areas under the canopy at specific points of the day.

5.3.3 Principle of the tailored venation algorithm

The leaf venation patterning previously described is tailored according to limiting geometrical conditions from the timber trade in order to fulfil the previously described parallel objectives of the project.

The outcome is a bespoke venation algorithm which is based on the placement of both auxin triggers and the seeds from which the growth originates. Within the algorithm are the geometrical conditions encoded through the following conditions. These include the notion of a continuous growth that terminates in either self or foreign intersection, a limitation to planar growth to facilitate planar assembly, limitations on angles and lengths according to both inherent material constraints as well as trade specifications in timber manufacturing and construction. Finally, kinks are restricted for structural purposes.

In a simplified manner the inner functions of the tailored venation algorithm loop continuously through the following algorithmic logic:

1. Find the closest seed for each individual auxin.
2. If an auxin is closer than an assigned distance to a seed this auxin

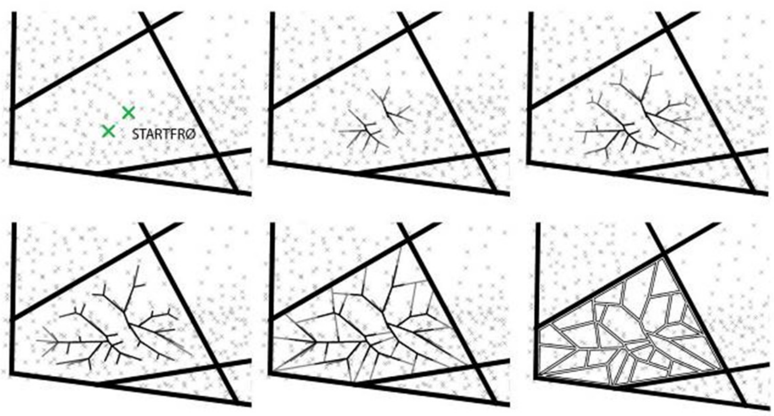


Figure 3.6: The growth of cassettes based on solar analysis and constraints from timber industry. (Henrik Evers)

will be removed from the set.

3. The mean vector from this parent seed to its child auxin location points is calculated.

4. A field of view based on the previous transformation vector (if any) and the angle constraint is set up.

5. If the mean vector is within the field of view the former transformation vector is passed on or in the case of not having a former vector the mean vector for the child auxin will be used

6. If the mean vector is outside the field of view the child auxin get separated into three subgroups based on their angular relationship to the seed. This makes it possible to assign a maximum angle for the venation algorithm.

7. If the child auxin are separated into the central field and a side field, one transformation vector is calculated for the side field. And another transformation vector is calculated for the central field if the length constraint is met, meaning that an assigned amount of the same transformation vector already has passed on this seed. If not the previous transformation vector is passed on.

8. If the child auxin are separated in the two side fields, a mean vector is calculated for each section and set as transformation vector, if the length constraint is met.

9. If all child auxin are in one of the side field of views the seed transformation vector is calculated from the last branching point to

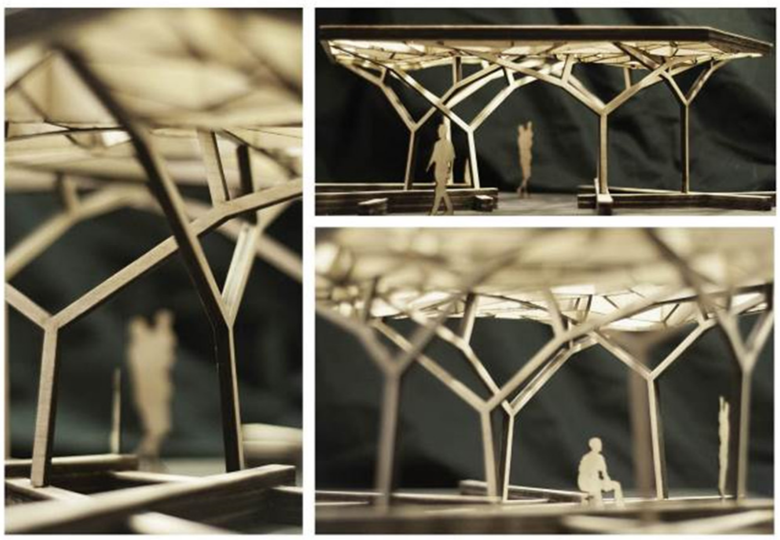


Figure 3.7: Pictures of model of physical outcome of study - wooden canopy. (Henrik Evers)

After all auxin are reached and removed from the set, branches continue to grow based on the last transformation vector until they intersect with other branches or foreign elements. This step is necessary in order to avoid hanging branches. This closing of the individual components ultimately activates the structural network.

5.3.4 Developing the setup for the generative algorithms

As mentioned, the structural system and light situations exist within this study as parallel objectives which are sequentially linked together in a generative system for the purpose of studying the behaviour of the tailored venation algorithm. This is addressed through two different approaches: 1) Post-growth analysis and evolutionary multi-objective optimization and 2) Pre-growth analysis and condition setup.

Structural systems: Post-growth analysis and evolutionary multi-objective optimisation

Although we observe that the venation algorithm as currently described finds a sufficient solution within the given constraints, the question remains whether better alternative solutions exist in parallel. Evan Greenberg describes in the paper Observation, Analysis, and Computation of Branching Patterns in Natural Systems, that ‘a recursive evolutionary algorithm can be implemented to correctly simulate dynamic parameters.’[7] In our case a post growth analysis and optimization through an evolutionary solver seeks for better results through the automated change of initial growth conditions and an evaluation step through FE-Analysis.

Evolutionary multi-objective optimization has been studied since the 1980s and up through the 90s evolutionary multi-objective optimization demonstrated the capabilities to approximate the set optimal trade-offs in a single optimization run. This sparked an interest in these evolutionary optimization algorithms and around 2000 a few elitist multi-objective evolutionary algorithms were presented. Amongst those were the SPEA – Strength Pareto Evolutionary Algorithm; which recently has been further developed in the SPEA2 algorithm. The basic operation of these evolutionary optimization algorithms is enacted as asearch through a mating selection and an environmental selection for an approximation of the Pareto-optimal set. This involves two objectives: both the distance to the optimal front is to be minimized and the diversity of the generated solutions is to be maximized.

The SPEA2 deploys an improved fitness assignment scheme, using a nearest neighbour density estimation technique and a new archive truncation. This approach has shown great results compared to other recent evolutionary multi-objective algorithms. [8]

Due to time constraints we later change the SPEA2 base multi-objective optimization with the Galapagos evolutionary solver, in the visual scripting plug-in Grasshopper for Rhino. Although the solver works in a similar fashion, it can only handle one fitness value. Hence we develop a formula in order to weigh different fitness values before they are combined and fed as single number into the solver.

This approach proves to be sufficient for the purpose of these tests, but for a finer grained multi-objective optimization it is certainly not robust enough. This calls for the integration of a SPEA2 or similarly multivariate capable based algorithm in future developments.

Light controlling systems: Pre-growth analysis and condition setup

The favored light conditions are determined prior to the generative process. This pre-growth analysis sets the conditions for the growth algorithm and in so doing calculates the initial locations of the seeds and the auxin.

The pre-analysis in this study is a sun and shadow analysis done through daylight simulation software. The desired amount of light at specified time intervals of the day is defined at the ground level and through a reverse engineered analysis of daylight a color map is developed at the level of the canopy. From this color map and the specified time of the day the auxin and the seeds are placed in a way that the tailored venation algorithm will produce a branching structure that provides the shade needed. (Fig 3.4)

5.3.5 Running the sequential design system

The overall design is split into two parts, each relying on its approach for the deployment of the tailored venation algorithm. These two parts are then sequentially connected.

Generating the load-bearing columns

The first part of the system handles the assembly's load bearing components. Here the venation algorithm executes column generation with a post-growth evolutionary optimization based on a structural FEA. The design process is comprised of the following steps:

1. The design boundaries in this part of the study are set up by the user, who defines the outer boundary of the canopy, the areas on the ground where columns are allowed to be positioned, and material specifications and dimensions.

2. The system automatically sets up beams spanning the canopy (or it uses a user defined starting point for the beams with a restriction of the deviation from these), auxin are placed on these beams and seeds within the dedicated areas for column placement.

3. The tailored venation algorithm runs and grows the columns.

4. The generated columns and beams run through an FEA simulation. The resulting moments in the joints and the maximum deformation are then fed into a formula to combine and weigh them against each other. The resulting fitness number is fed into an evolutionary solver and a iterative process is initiated to optimize for the highest fitness values. (Fig 3.5)

5. The loop stops when a desirable fitness value is reached

Generating the light filtering canopy

Based on the structural setup the structure of the canopy is developed. This takes place in the spaces between the previously determined beams.

Based on their geometry a solar analysis determines their impact on the environment, which is overlaid with the desired map of solar intensities in different areas at different time intervals. The result is a pattern of auxin and seeds. The auxin are denser in areas with shading capabilities and the seeds are laid out in lines according to the solar vector at the time of the day when shading from that specific area is needed. This ensures a close-to-perpendicular growth for optimal shading at specified time intervals.

The tailored venation algorithm grows the cassette-filling planks, whose height is set according to the solar analysis.

5.3.6 Conclusion

The study shows that biomimetic algorithms can be customized in such a way that they successfully negotiate the potentially contradictory parameters derived from formal, energy-based, structural, material and construction-based design parameters. Yet an easy-to-grasp interface for this procedure is enabled by the growth venation algorithm, and controlled through a design driven mapping of auxin. As a result, the initial auxin setup becomes an indirect transmitter of information and serves as a starting condition that can be written to as well be read by the designer. This minimum information level guides the system of self-aggregating structures through simplified boundary conditions. However, although the map of auxin can then operate as the substrate for growth, these patterns nonetheless can be further informed through an optimization process. The necessary mechanism can be found in linked simulations – whether pre-generative or through a process of evolution. The auxin maps serve well as they are easy to manage, their density gradients easy to intuitively understand, and they bear the potential to be constantly updated.

This follows the lines of Evan Greenberg, as he states: 'by applying evolution to computational systems, an iterative process of modification can lead to an artefact developed in a simulated environment inclusive of certain limitations and fitness criteria.'[7].

5.3.7 Future development

The study uses a hierarchical approach to solve the overall problem: the structural level is solved first and informs consequently the canopy level. Both levels have a high degree of autarchy, with no feedback loop. A richer process of integrating interdependent feedback networks between the levels would may generate a more credible result.

A way to link these processes might emerge from a future inclusion of an embryotic state into the evolutionary process. This can in short be interpreted as the information channels through which different genomes to control the area and timespan of the activation of genes for growth as part of the internal intelligence of the embryo. This step of combining into evolutionary computing, more directly into with algorithmic branching systems, could allow for an optimization that is in result more similar to biological systems. [7]

One way of seeing this inclusion of embryology could be an integration of the two sequential parts into a parallel system with a continues continuous feedback loop operating throughout the growth algorithm. This may to correct local growth conditions and imbed embed intelligence while running. Additionally, a post multi-objective evolutionary optimization embedding may embed a higher level of intelligence through an automated iterative process and of evolutionary selection setting the initial parameter space for the growth algorithm.

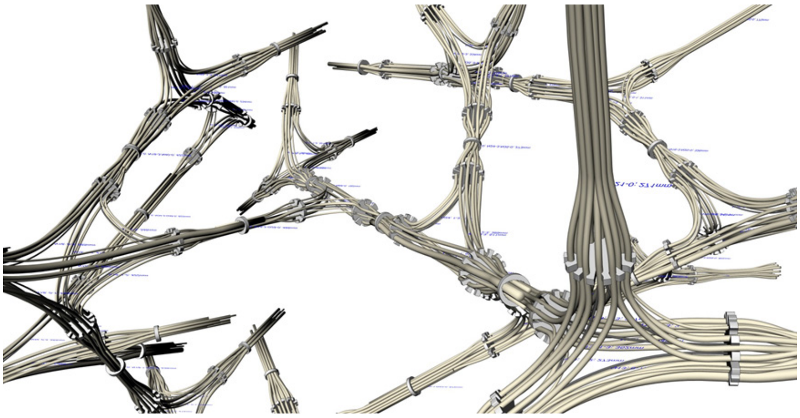
5.4 The Rise – integrating feedback for growth

In the research-based installation "The Rise" (Fig. 4.1), commissioned for the spring exhibition "ALIVE – Designing with Living Systems" at the Fondation EDF Espace in Paris, we integrated simulation and feedback to examine real-time material and structural behaviour in order to use the bending capacity of rattan bundles for structural purposes. Like a bush the 5m high installation has its own internal growth patterns that branch the material into a highly distributed aggregation from two growth sources. Similar to such plants as the strangler fig and other types of ficus, shoots can fuse in new circular relationships, creating both structural strength and additional infrastructural network pathways that enable the networked system to reach its goal with a minimum of material.

The biomimetic model interrogates and collapses the discretized design cycle described in the introduction of this paper such that both material intelligence and environmental sensing are embedded in a continuous particle-based physics simulation, calibrated through observed and measured real-world material behaviour. The simulation is interdependent with incremental topological reactions in the model geometry. Performance and behavioural

Figure 4.1: Detail of demonstrator "The Rise" in Paris, showing rattan bundles managed by HDPE "packing nodes" and the rattan deployed in oppositional active-bending branching moment connections as organized by HDPE "stars". Photo by Anders Ingvartsen

Figure 4.2: Computationally generated digital model of rattan struts and connection nodes as organized by HDPE "packing nodes" and "stars".



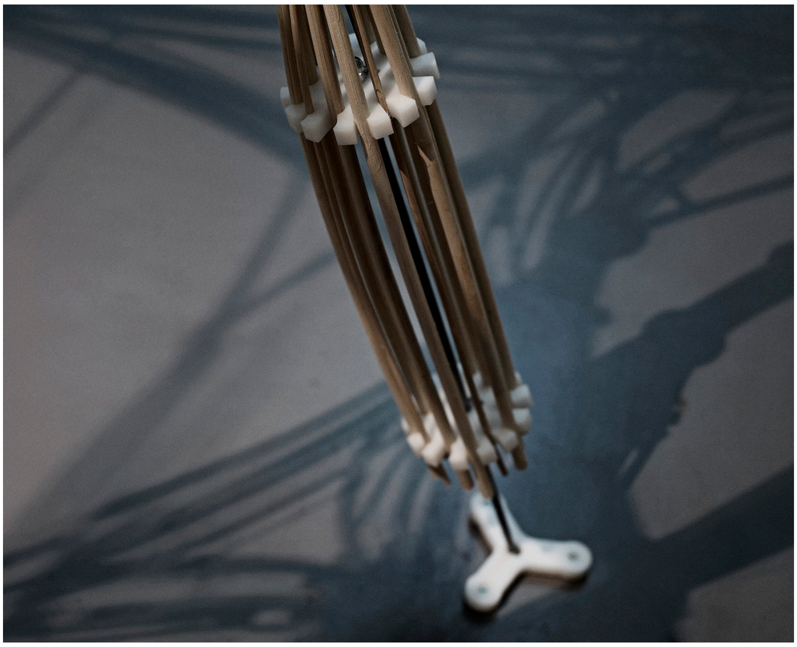
analyses are fully integral to this time-based sensing/growth/material simulation algorithm. This approach opens the possibility of developing a modelling system that can become aware not only of the environment, but of its own reactions to external stimuli.

The generative design and fabrication systems developed for the 1:1 demonstrator of "The Rise" reflect a synthesis of multiple research questions related to:

1. The on-going investigation of material performances and structural behaviours in differentiated active bending assemblies [9].

2. The deployment of novel digital physics-based simulation processes for accretive morphogenesis and the interrogation of dynamic parameter spaces.

Figure 4.3a: Steel rod and ball joint detail activated by "thigmotropism" in the generative algorithm, used in climbing and secondary environmentally responsive connections. Photo by Anders Ingvartsen



3. The development and application of biomimetic systems.

Each of these questions is related to different aspects of both CITA's continuing lines of inquiry into the computation of wooden structures [10,11] and the design brief associated with the exhibition for which the final object is commissioned. This subject – the use of biomimetics in architectural design – provides the conceptual foundation for iterating through multiple methods for "growing" and testing structures, and from this emerges a set of interdependencies related to material choices, digital form-finding, behavioural simulation, and methods of detailing.The adaptive growth algorithm and continuous physics-based material simulation deployed through the generative model work in concert to activate the characteristics of the rattan core as primary contributors to morphogenesis and enable an algorithmic procedure that is informed by both self and environmental awareness. "The Rise" has been developed to behave like a climbing growth organism. It utilizes structural shoots and gripping feet that identify and cling to their physical surroundings as vine-like plants do. Additionally, it achieves structural triangulation through a process of self-grafting.

5.4.1 Material systems

As a material assembly, "The Rise" is comprised primarily of rattan and high-density polyethylene (HDPE), and secondarily of steel and aluminum. The woody, fibrous rattan members perform multiple roles. They provide the installation's primary structure as bundled struts which then strategically split

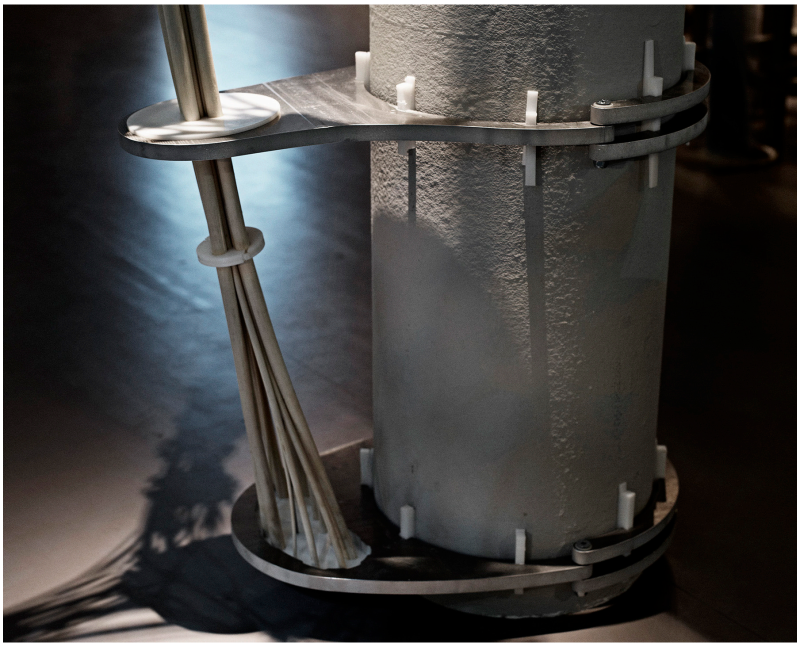


Figure 4.3b: Aluminum "column hugger" collar system, utilized for securing the installation at its two primary growth "seeds". Photo by Anders Ingvartsen

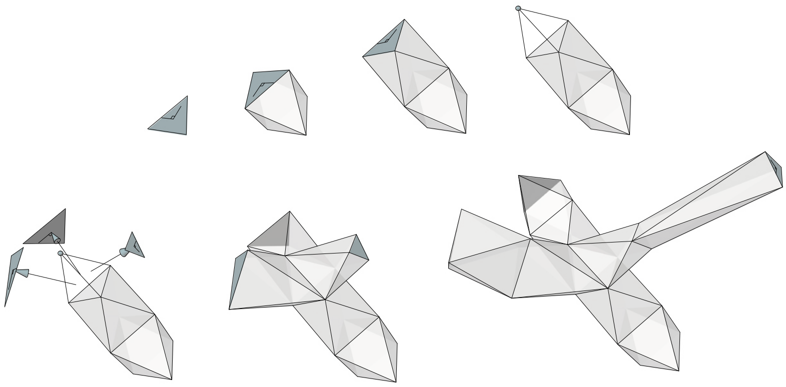


Figure 4.4: Minimally triangulated modular accretion and branching processes for simultaneous management of spring-based system and model topologies that register bespoke geometric relationships developed from the growth algorithm

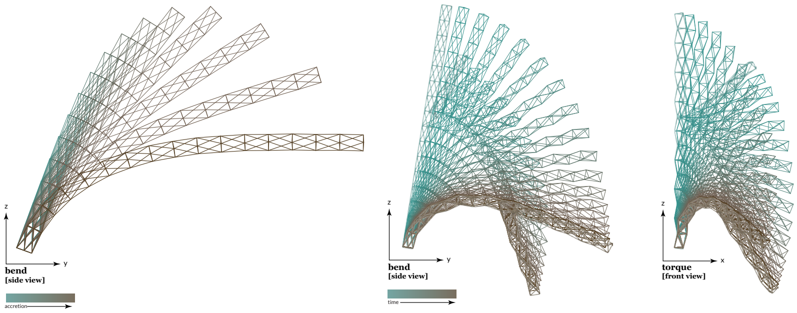
apart to engage in a geometrically varied branching moment-connection detail that operates in oppositional bending. Additionally, a secondary system of rattan "guide posts" is used to enable the installation to self-jig during assembly. The members range in length from approximately 1m to 5m and sectional diameters of 4mm for the "guide posts" and 5mm, 10mm and 19mm for the primary structure. The HDPE is deployed as a series of bespoke CNC-milled circular plates – referred to as "packing nodes" and "stars" – that respectively bundle and split and orient the rattan fibres (Fig 4.2).

A steel rod and ball joint detail (Fig 4.3a) and an aluminum collar system (Fig 4.3b) are separately used to connect the installation elements to the exhibition space.

The rattan sourced for the installation is sustainably harvested in Malaysia, where the wood is knife-extruded into round sections. Rattan is soft and is comprised almost entirely of a collection of continuous, tightly packed hollow fibres which enable efficient transfer of water and nutrients, rapid growth and extreme bending [12]. The rattan is identified as the material of choice for several reasons. Most crucially, at the scale of the installation, its extreme pliability makes it highly suitable for our investigation into continuous material simulation during the modelling phase. Its sustainable, organic nature fits furthermore the exhibition brief calling for a biomimetic design system, as do the nested hierarchies reflected in its multi-scalar bundling at both cellular and assembly system levels.

5.4.2 Integrating morphogenesis, calibration and fabrication

Material properties in "The Rise" are embedded as part of the digital modelling process. The use of a centralised geometry system for the navigation of multiple



Figures 4.5a & 4.5b: Spring model as it accretes additional modules and demonstrates incremental bending under increasing self-weight and length; Spring model exhibiting torque/rotation due to asymmetrical loading/ orientation of branches combined with bending

design priorities proves crucial in this regard as careful management of model topology enables the integration of the continuous physical simulation with all aspects of the recursive morphogenetic growth algorithm (Fig. 4.4). But this careful topological strategy is simultaneously essential for its provision of a clear platform to calibrate the digital processes according to observations of physical experiments, and ultimately for managing the production process, sizing of members, and detailing of all aspects of the structural fabrication systems.

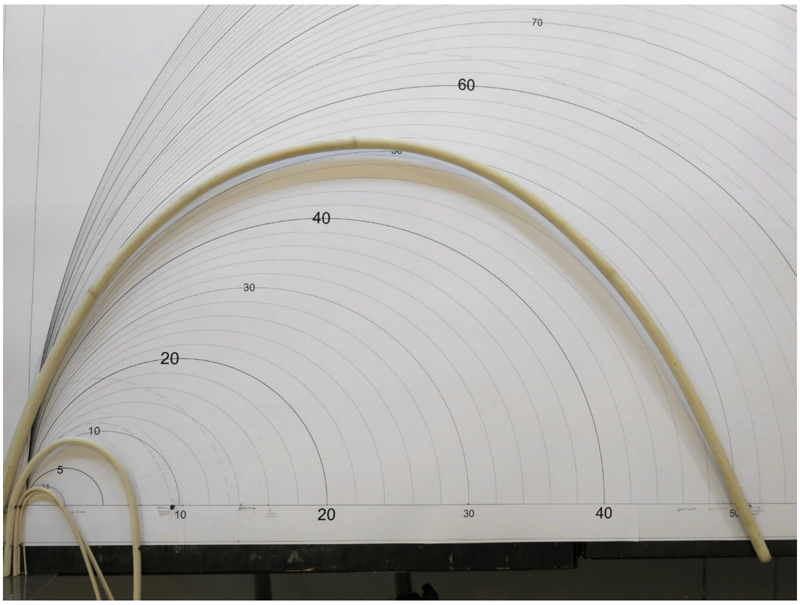
Morphogenesis

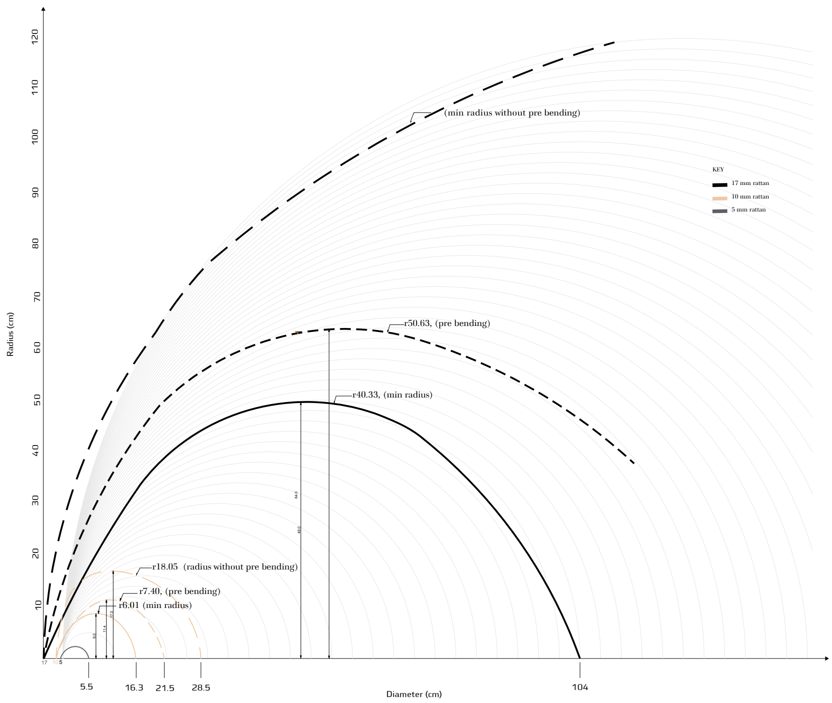
Some of the primary features of the model's growth process are its capacity to branch and graft. These model transformations are defined structurally by geometrically bespoke moment connections that allow for the model to actively seek goals defined by the design algorithm's response to its environment, which include reaching toward the light or back to its surroundings for structural support. The aforementioned demand that the material characteristics be reflected during the growth process combined with the on-going need to utilize output for both calibration and fabrication leads to the testing and application of a minimally triangulated truss-like model assembly expressed in a mesh. The springs are managed using the mesh vertices as individual particles to which mass and gravity forces are applied, and the mesh edges are characterized as a system of springs. The triangulated modules are allowed to accrete and branch according to virtual energy accumulated during the simulation. Each stage of accretion is defined as an incremental module. Each stage of branching is defined by the growth tip being raised into a tetrahedron whose new faces define the tips for three new faces.

Calibration

The abstraction of individual bending members in the design and simulation model by means of an axis line seems to be generally appropriate and robust for even more complex active-bending assemblies [13, 14]. However,

Figure 4.6: bending radius and member failure as a function of section and pre-stress duration. (Hollie Gibbons)





in the case of "The Rise", due to the dominant asymmetrical loading and cantilevering conditions during the morphogenesis, out of axis forces have a significant impact on the deformation figure of the elements and have hence to be considered. As a simple line-based model cannot compute the emerging torque and rotation of the assembly the members in "The Rise" were modelled in a truss-like configuration. This allowed the model to adjust to both the open-ended nature of the algorithm and the accretion during the generative phase (Figs 4.5a and 4.5b).

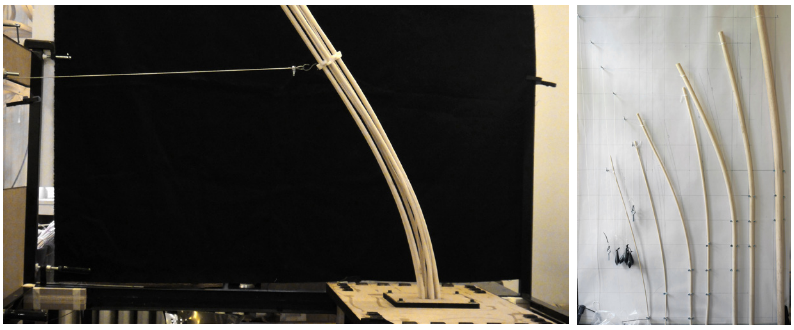


Figure 4.7: measuring multiple rattan thicknesses and bundling configurations bending under variable loads. (Hollie Gibbons)

A series of physical tests are performed and used for calibration of the computational modelling development. These examine the behaviour of rattan members in bending, both in the practical determination of minimum radius according to each section used in the assembly process (5mm, 10mm and 19mm) (Fig 4.6), as well as for the empirical observation of deformation in bending with variable loads and individual and bundled configurations (Fig 4.7).

Equipped with these observations, the growth algorithm is executed. As each growth iteration and simulation cycle is processed, the digital generative model generates a body of output data to be used for on-going analysis and as direct input to the fabrication model. These data supply information regarding local spring deformation associated with the topology of each branching, grafting and climbing moment. The topology of each branching event is captured through carefully a managed data structure that houses the final fabrication model geometric bases as a series of aligned planes, individually arrayed according to each of these critical moments. It is through the data structure that multiple, interdependent fabrication drivers are specified and coded, including: information designating variable connection types (including regular branching, grafting, and structural tie-back), strut connectivity assignments, assembly sequencing, and member sizing.

The spring deformation data are registered specifically for the purpose of assigning material thickness to each connection node such that it is capable of managing local compressive and tensile stresses (Fig. 4.8).

These local forces must be managed in concert with a branching moment connection that achieves its architectural expression, geometric configuration and structural performance as a collection of rattan members operating against one another in oppositional active bending. Through a series of analyses and prototypes both digital and physical, a system for synthesizing these performance characteristics in fabrication emerges (Figs. 4.9).

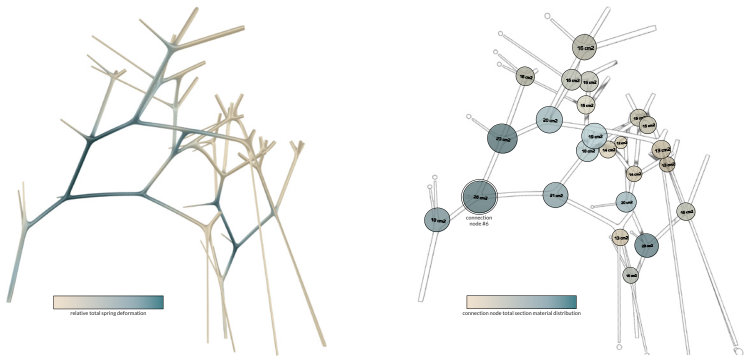


Figure 4.8: Generated model registering varying degrees of spring deformation and translated to assign total sectional thickness for each connection

Prior to the design and detailing execution for the final installation in Paris, a series of 1:1 prototypes is built at CITA. The final calibration of the sectional thickness assignment strategy that is deployed for detailing the installation is executed through both direct observation and measurement of the material behaviours and comparisons of a 3D scan to the digital prototype model.

Fabrication

The process of material assignment within each connection begins with analysis of each of the branch struts in relation to one another. In a four-strut connection node, there are a total of six oppositional angles and topological relationships to design for. The fabrication model examines these relationships, and based on the size of each angle in relation to the others in the connection node, the total material determined for the connection node is distributed to approximate the desired geometric configuration. Generally speaking, this means that material assignment to narrower angles is lower as they must bend more, and that to wider angles it is greater, as additional resistance results in lower bending. This total thickness assigned to each topological relationship is then translated into a collection of individual members of varying thickness (Fig. 4.10).

Finally these data are translated into the configuration of the individual "star" elements in each connection node. The unique profile curves for the CNC-milling of each are generated according to this topological distribution of the individual rattan members (Fig. 4.11). These outputs include full numbering systems for tracking each member and the geometric data that feeds a series

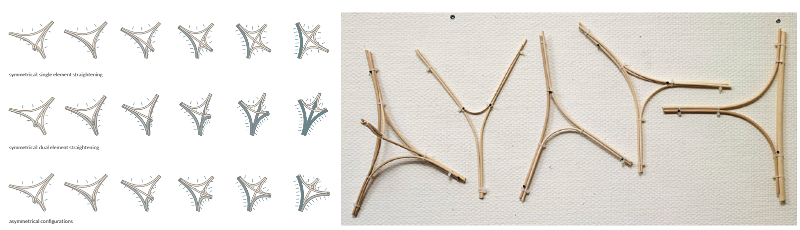


Figure 4.9: Digital and physical examples of oppositional active bending and connection node geometric responses resulting from variable thickness/bending stiffness of specific elements

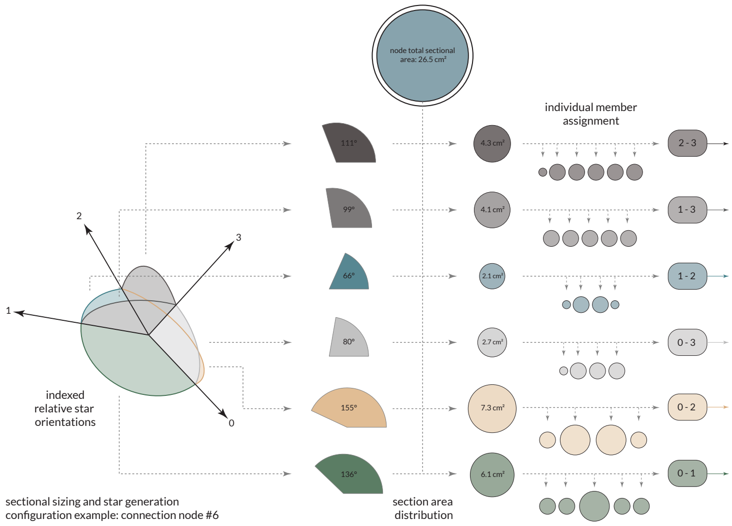


Figure 4.10: Connection node development: connectivity/topological assignments, geometry analysis, total sectional material allocation, and individual member assignments, and final star configuration for connection node #6

production of drawings to be used during the installation process. Each of these elements is also projected back into a fully detailed and computationally generated 3D model for both verification and reference during assembly.

With the sizing and orientation of each rattan member in the installation determined according to the branching moments, a system for the deployment of the "packing nodes" and for ensuring continuity between connection nodes is executed. This process again relies on the data structure supplied from the generative model and utilizes the organization and formation of the related "stars" between each connection node.

With the size of each local connection member calculated and geometrically

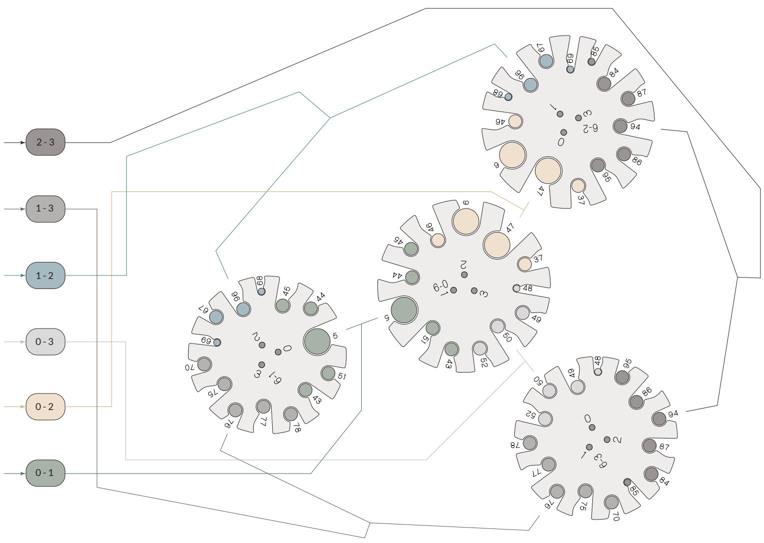
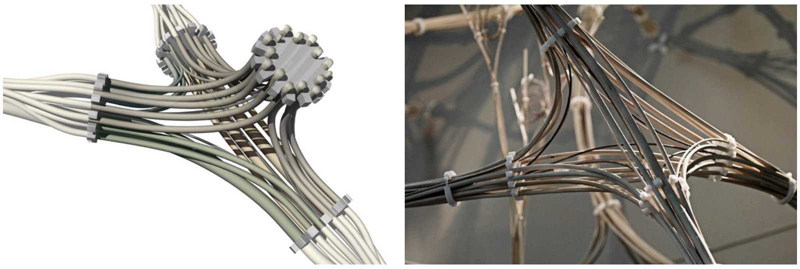


Figure 4.11: Topological array of individual rattan elements across each bespoke CNC-milled HDPE "star" element within connection node #6

Figure 4.12: Digital representation of connection node #6 and the physical manifestation of connection node #17, demonstrating two different, bespoke branching geometries achieved through variably-sized and numbered oppositional active-bending rattan members, managed through the HDPE "star" configurations. Photo by Anders Ingvartsen



assigned through the connection node development process described above, each strut is able to test for possible rattan member continuities.

The sections of the members for each star that share a single strut are projected to an average plane and tested for proximity to an identically sized member in its counterpart. Each member's candidacy for continuity is determined first by this proximity, and secondly according to the limits of the material length. So while the algorithm identifies certain members that could run for up to 10m, based on these material constraints, for this assembly the longest members are allowed a length of up to 5m in total. Non-continuous members through each strut overlap and terminate, while continuous members thread through each connection node, and sometimes beyond through several additional connection nodes (Fig. 4.14). With the final determination of unique members that pass along each strut complete, a circle packing simulation is executed to form the bundling logic for the strut. This logic is captured and translated into an additional bespoke CNC-milled HDPE "packing node" unit (Fig. 4.13).

Conclusions and Future Developments

"The Rise" demonstrates the potential for using design systems based on ideas of growth to develop working structural systems in a changing environment. It

Figure 4.13: rattan member continuity testing and the development of bespoke "packing nodes" along the strut connection between connection node #6 with and connection node #13

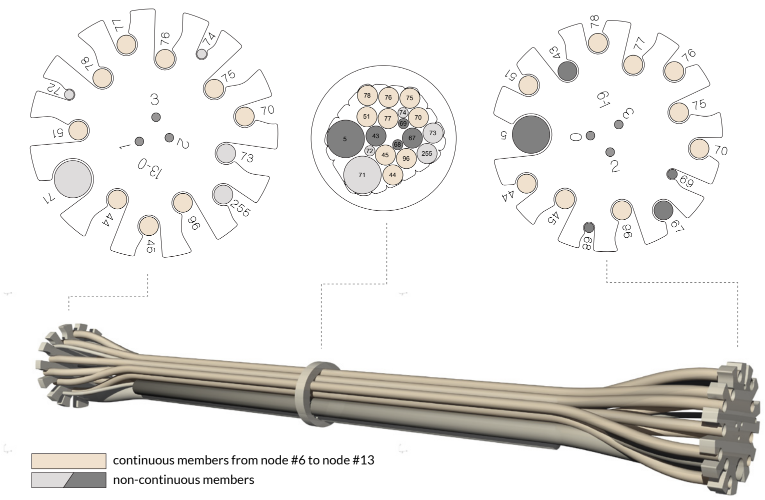


Figure 4.14: tracking member continuity for all rattan members that pass through connection node #6

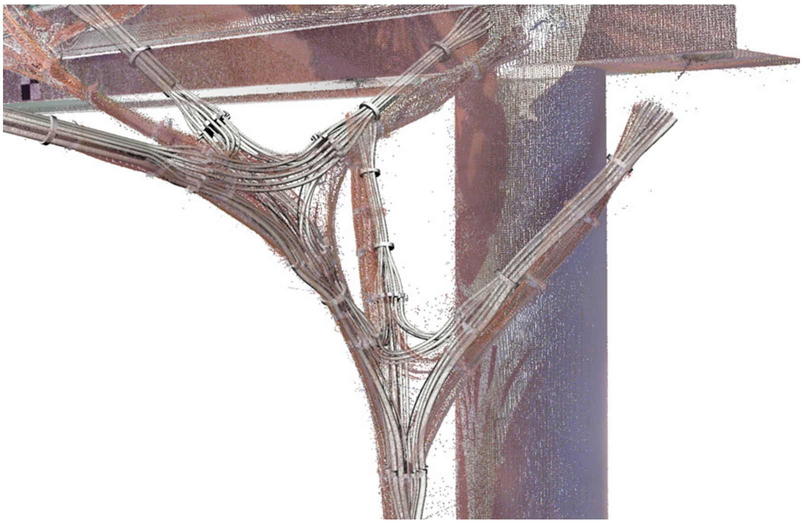
achieves this by collapsing the space between generation, simulation, analysis and feedback and reducing the distinction between each to a brief moment of internalized computation. Through this, morphogenesis is accomplished in a system able to directly couple generative strategies with material behaviour and consequence, such that iterative stages of accretion and organization directly rely on previously accumulated geometry and its simulated performance characteristics.

There remain a number of opportunities for further exploration of these systems. Through the use of 3D scanning, analysis of the final installation geometry as compared to the digital model reveals the most significant source of the discrepancy as the configuration strategy deployed at each connection node. A better understanding of the geometric principles associated with oppositional bending of variable sectional elements will allow for greater fidelity. The idea of fully integrating simulation practices during morphogenesis suggests that in an idealized manifestation of such an approach these processes should extend more directly to the fabrication system as well. Nonetheless, "The Rise" establishes itself as a proof-of-concept for deeply embedding material simulation in the generative modelling process, with the aim of collapsing the iterative cycle such that topological transformations to the model are continually registered through the filter of both environmental sensing and behaviour.

5.4.3 Conclusion

Within this paper we have shown two architectural studies that employ algorithms based on vegetative growth patterns to generate wooden structures.

Figure 4.15: Comparison of digital model to 3D scan of final installation. (Martin Tamke)



Both take their point of departure in approach to include properties, behaviours and constraints from material, construction and environmental considerations, not literally but in the depth of their generative level.

Simulation

Both studies are similar in their approach towards the mapping of the parameter space. Where the canopy study focuses on a dialogue with architects, engineers and craftsman to define the limiting parameters, "The Rise" enters a new territory and has to create first the underlying knowledge-space through probes and prototypes. The knowledge space is in both tied to design, acknowledging that certain aspects lack precision and that these existing gaps must be patched with assumptions. Though speculative in nature, both studies offer a clear trajectory for a further refinement with more advanced simulations and testing, up until fabrication and assembly, which was successfully implemented in Paris.

Within the projects the established role of simulation in architectural design is challenged, as both endeavour to integrate the simulation and generative processes into a cohesive and continuous whole. The necessary output of the simulation is here a credible behaviour. Approaches that take their point of departure in material properties [11] are here inappropriate – as too detailed. The calibration of a simulation system is here seminal for the design process, although it might not be bound in the first place to the material it is actually simulating. The calibration of these systems through relatively basic testing setups that are able to capture the behaviour of elements rather than their distinct individual properties allow us to successfully realize the aims of both projects. In the future, the behaviour of the test setup might also be used to

Figure 4.16:"The Rise". Photo by Anders Ingvartsen

calibrate a detailed FEA model. From this a wider set of limiting parameters might be derived – a set that was missing for instance for the detailed definition of maximal stresses in the generative process of the first study.

Future development for work with vegetative growth algorithms

In our work with algorithms based on vegetative growth patterns we observed the benefits of a model where topology can be reconsidered in every growth step. Here the parameter space can be seen as both dynamic and adaptive during morphogenesis. This tightly bound but open process helps negate the determinism reflected in models whose design cycles generate fixed model topologies prior to activating various modes of simulation, including both physics-based form-finding strategies and post-formation analytical simulation systems, such as for finite element assessment or environmental performances. In such models, the adjustments to the parameter space occur between complete morphogenetic iterations. Of course this strategy has been demonstrated to be highly robust, not only through standard methods that rely on designer intuition for refinement, but also through the application of such performance optimization techniques as genetic algorithms or neural networks for the modification of parameters between iterations. Indeed, for the timber canopy project discussed in this paper, such a strategy is effectively deployed. But the integration of simulation as part of an accretive modelling technique presents an alternative approach and a means to allow for more continuous, localized responses within the parameter space to conditions that emerge during the morphogenetic process. Furthermore, it may be possible to integrate this approach with various optimization algorithms, potentially allowing for the evolutionary processes they emulate to register variably over the course of individual model iterations rather than between them. In these projects, it is the emulation of energy metabolism and tropism-based algorithmic branching network growth processes that catalyses this approach.

Acknowledgments

The project was only possible through a wide set of dedicated collaborators and supporters: Krydsrum Architects / Copenhagen, Mette Ramsgaard Thomsen, Hollie Gibbons, Shirin Zhagy, Carole Collet, The EDF Foundation, The Danish Agency for Science, The DuraArk project by the European Commission within the 7th Framework Programme (Grant Agreement no: 600908).

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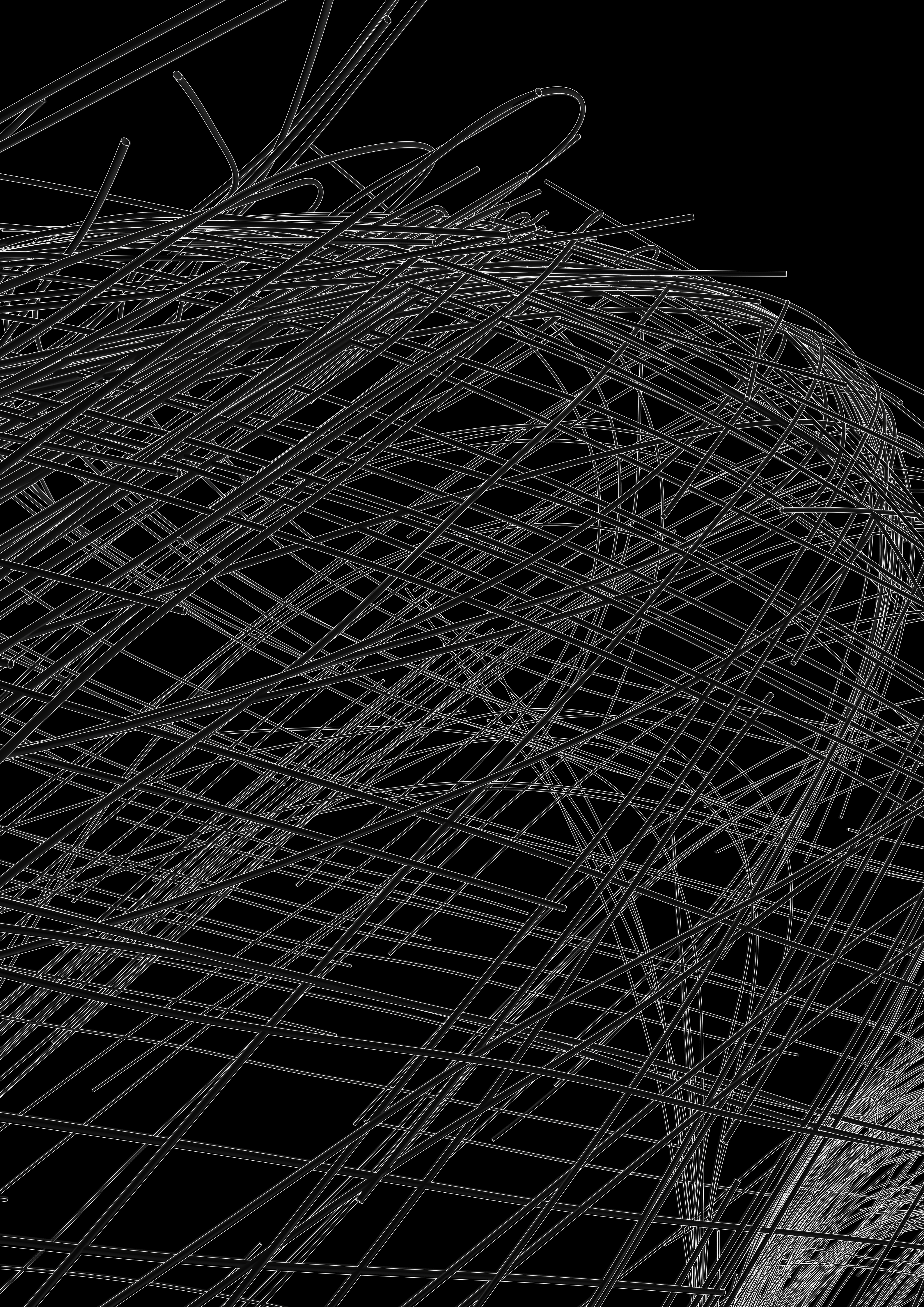
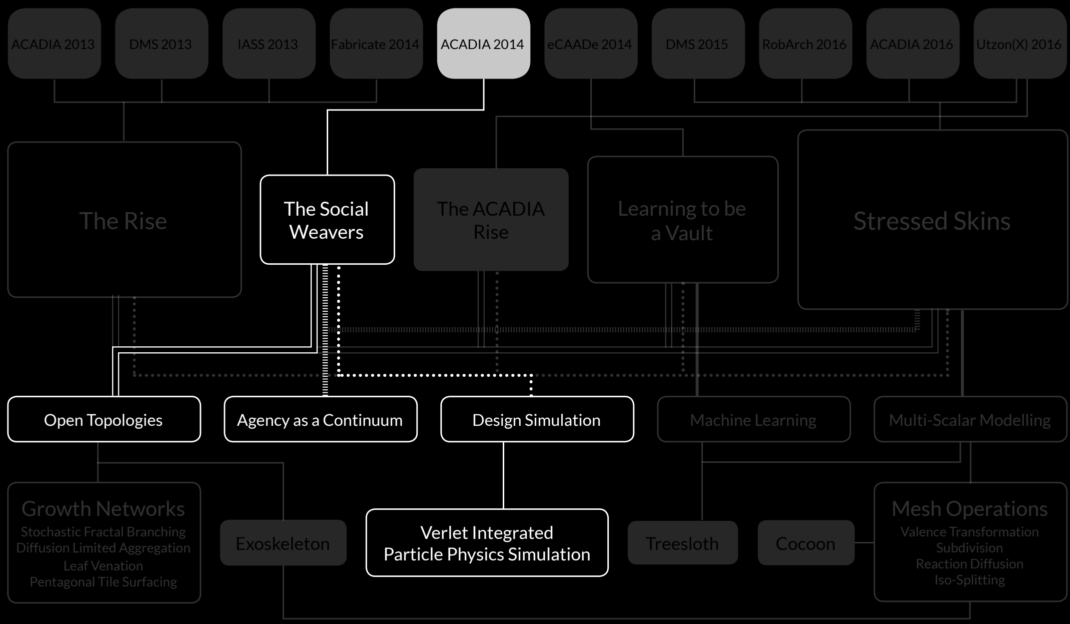




Publications II: The Social Weavers

The publication presented here is related to my role in the development of the modelling system for *The Social Weavers*, a research installation developed as part of a master class/ workshop held at Monash University and led by Paul Nicholas and Tim Schork.

> Nicholas, P., Stasiuk, D., & Schork, T. (2014). *The Social Weavers: Considering top-down and bottom-up design processes as a continuum*. In Design Agency [proceedings of the 34th Annual Conference of the Association for Computer Aided Design in Architecture] (pp. 497-508).

Engaging with Open Topologies, Design Simulation, and Design Agency as a Continuum

Both open topologies and design simulation remain topics of central interest throughout the experimental work that constitutes the chief substance of this research project, and in this context *The Social Weavers* endeavoured to extend the work initiated in *The Rise*, particularly regarding the effective collapse of the morphogenesis and the simulation of material properties, better integrating formation with matter-based concerns and enabling adaptive reparameterisation through the adaptation of underlying data structures that defined the collection of assembly elements through the dynamic activation of their simulated behaviours. This extension was tied to not only enabling the designed forms to simulate in the digital design space the material properties they should physically exhibit, but furthermore to enable the material specifications to be adjusted during morphogenesis. This feature had been lacking in modelling system used in The Rise and its implementation became a topic of focus to further demonstrate the adaptability of open-ended design systems, allowing not only for real-time expression of general material properties, but also to provide direct and active feedback regarding the exact characteristics of each assembly element.

Furthermore, however, emerging as part of this experimental project was an epistemological concern that defines a central theme for this thesis project in total, which is tied to re-understanding what are normally considered as discrete classification systems rather for their continuous nature. This paper examines this phenomenon specifically as it concerns designer agency, first contrasting the tendencies exhibited by “top-down” versus “bottom-up” approaches to generative, algorithmically-driven modelling systems. It then presents a theoretical model for reconciling the apparently binary nature of these approaches and uses the modelling system of *The Social Weavers* to demonstrate an alternative understanding of agency that synthesise top-down designer direction and understanding of problem spaces with the potentials for the types of computationally increased design intelligence that are uniquely realised through accretive, open-ended, and simulation-driven morphogenesis.

Methodological relevance

This concept of redefining descriptive systems whose constituent elements are typically understood as categorical in nature into continuous systems becomes central to the general methodology presented through this thesis. This is first predicated on the assertion that modelling setups for projects of even the most modest scale are complex enough to require multiple partial models for their realisation. As each of these partial models is assigned its own functional or epistemological purpose, it becomes important to articulate aspects of their formulation: understanding how and why discrete model elements are developed and deployed is an essential feature of complex modelling practice. Unlocking categorical descriptions into continua affords designers with much greater nuance not only in describing modelling systems, but also in the applicability of the models themselves.

Project role

My principal role for this project was as the lead developer of the design modelling system used within the workshop. The aim was to create in advance of the workshop a fully-realised design modelling platform that participants could use to explore and iterate design for the development of a physical installation. Unlike in *The Rise*, I did not participate in the development of physical prototypes or in the production of fabrication models. However, the design modelling systems developed were created with eventual applicability toward facilitating efficient and accurate fabrication representations.

Author role

My contribution to the publication is broad. I authored the technical portion of the paper that focuses on the modelling and simulation systems used for *The Social Weavers*. Additionally, I contributed significant portions of the text that present and reflect on the theoretical frameworks concerning motivation, research questions, and findings.

Presentation

The paper presented here has been reformatted for continuity, but all textual and visual content remains unaltered from its original, peer-reviewed presentation.

6. The Social Weavers: Considering top-down and bottom-up design processes as a continuum

Reformatted from: Nicholas, P., Stasiuk, D., & Schork, T. (2014). *The Social Weavers: Considering top-down and bottom-up design processes as a continuum*. In Design Agency [proceedings of the 34th Annual Conference of the Association for Computer Aided Design in Architecture] (pp. 497-508).

Abstract

Predictive architectural models have, over recent years, become able to integrate material feedback by incorporating either finite element or physics-based simulation processes. When used to simulate large material and structural deformations, they can be informed by both specific material properties as well as formal mechanical behaviours, for the purpose of calculating and representing material characteristics over time. However, in many commonly used modelling approaches, this increased influence of material is achieved only at the expense or limitation of other agencies: those of the designer, of the design space, and the assembly.

As our design processes increasingly navigate complex, open-ended design spaces, finding effective methods for extending agency becomes a growing architectural preoccupation. The research presented here describes the context

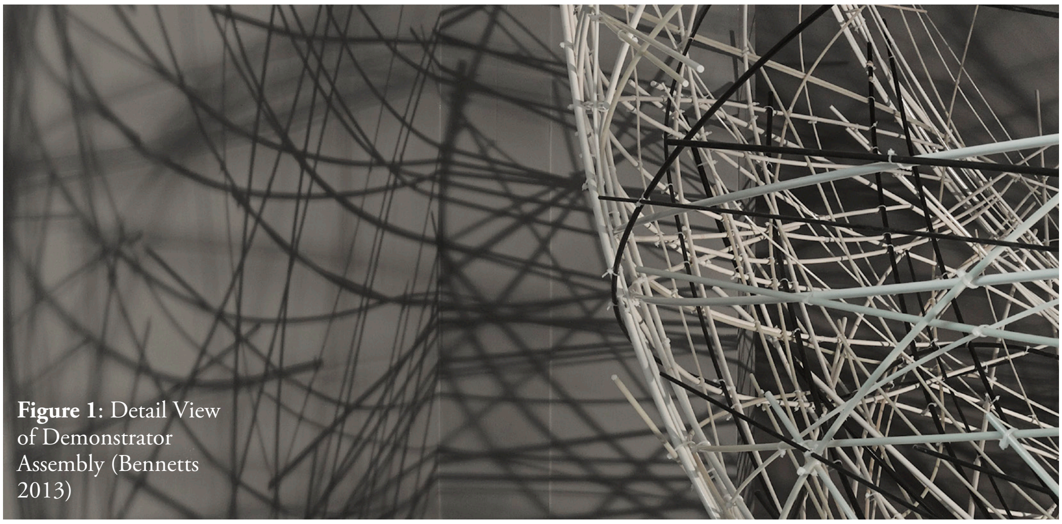


Figure 1: Detail View of Demonstrator Assembly (Bennetts 2013)

of open-ended design spaces, and distinguishes between two characteristic modelling approaches: designer-controlled simulation models that exhibit material agency but are constrained by topologically fixity (top-down), and simulation models that operate with unfixed topology but at the expense of direct agency for the designer (bottom-up). We identify this as a false dichotomy and present a third approach that treats this space as a continuum.

A built case study project demonstrates the underlying modelling concepts and methodology. "The Social Weavers" is a bending active, non-standard grid shell structure made from fibre composite rods of varied diameter and stiffness. The installation develops aggregate self-forming processes that intersect with the behavioural activation and distribution of fibre-composites under design direction for the production of a novel architecture.

6.1 Material agency through computation

Material computation is the activation and exploitation of agency within material. Materials have the capacity to process information, and if these behaviours are incorporated into digital design models, they become materially informed (Deleuran et al 2011). Digital models of this kind extend upon purely representational practices by incorporating iteration, simulation and feedback. They can encode behaviour-based relations between scales, materials and structures, and be used to specify material organizations and steer material behaviour.

This research focuses on a particular type of material agency: the activation of bending as a self-formation process. Bending-active structures (Lienhard et al 2013) use the capacity of material systems to self-organize under loading to generate three-dimensionally curved geometries from initially straight two-dimensional elements. Although this approach to making structures has a long history in vernacular architecture, few current built examples of bending-active structures exist. Frei Otto's Mannheim gridshell (Happold and Liddell 1975) remains one of the most prominent examples. The geometries that are possible for bending active structures are limited by the physical properties of the structural elements. For example, material and cross-sectional properties restrict the allowable curvature in the structure. Materially, bending-active structures must be flexible enough to deform and bend easily, with the capacity to remain elastic. They also need high strength, which makes their high curvature possible. Traditionally, timber has been the most commonly used material, however fibre-reinforced composites have a lower relation of stiffness to strength and are thus able to achieve higher curvatures.

Because of these considerations, the incorporation of material information, the prediction of transformation, and the steering of bending behaviour

Figure 2: Inhabiting the Structure of the Demonstrator (Nicholas 2013)

Figure 3: (Opposite) Plan and Elevation Drawings of the Demonstrator (Nicholas 2013)

become central to the design process (Lienhard et al 2013). Here, composites represent an opportunity to extend the specification and design of bending-active grid shell structures. They allow the development of high curvatures but also, because they are precisely specified and standardized in their mechanical performance, provide an opportunity for grading (Nicholas and Tamke 2012). Composite grid shells made from elements of varied stiffness introduce the possibility of customized structural rigidity, for the purpose of optimizing the calibration of loading, resistance and reaction in each element. An allowance for dynamic variation of material through agent-based decision processes is not normally part of the design process. Its consideration during this phase may expand the possibilities for desirable flexibility in the design as a whole.

6.2 Bottom-up and top-down

In the context of computational design modelling, the terms top-down and bottom-up are often understood in relation to one another as poles in a methodological dichotomy, with the former describing an explicitly-directed, fully-bound and centralized approach, and the latter an implicitly-directed, unbound and decentralized one. In this context, top-down design models exhibit deterministic tendencies, with global configuration criteria operating across the system and individual components responding to and embodying these directives. Bottom-up design models instead exhibit tendencies for step-wise dynamic morphogenesis, with the configuration of components functioning through agencies afforded by local intelligences and stochastic interdependencies between elements (Crespi et al 2008). The development of computational design models typically entails identifying and prioritizing one of these methods for implementation, based on some mix of suitability and conceptual orientation.

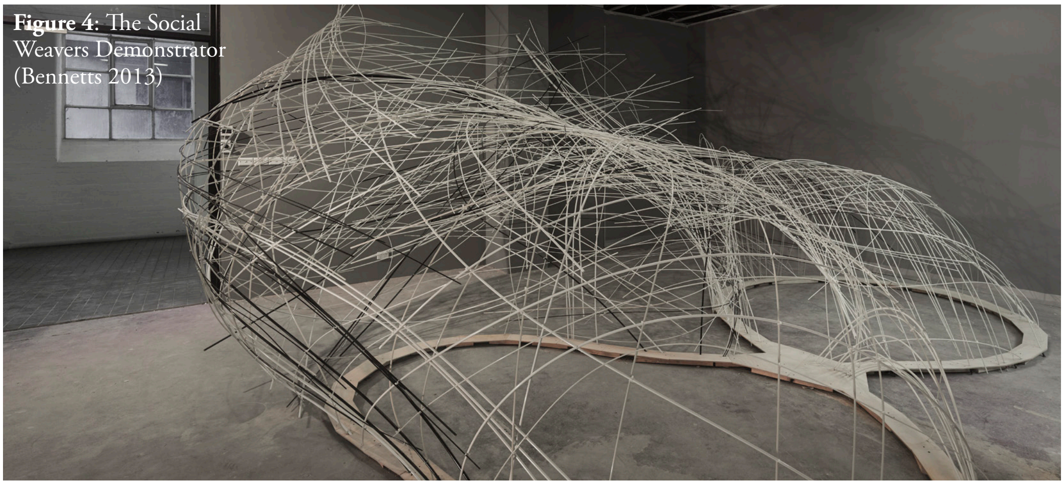
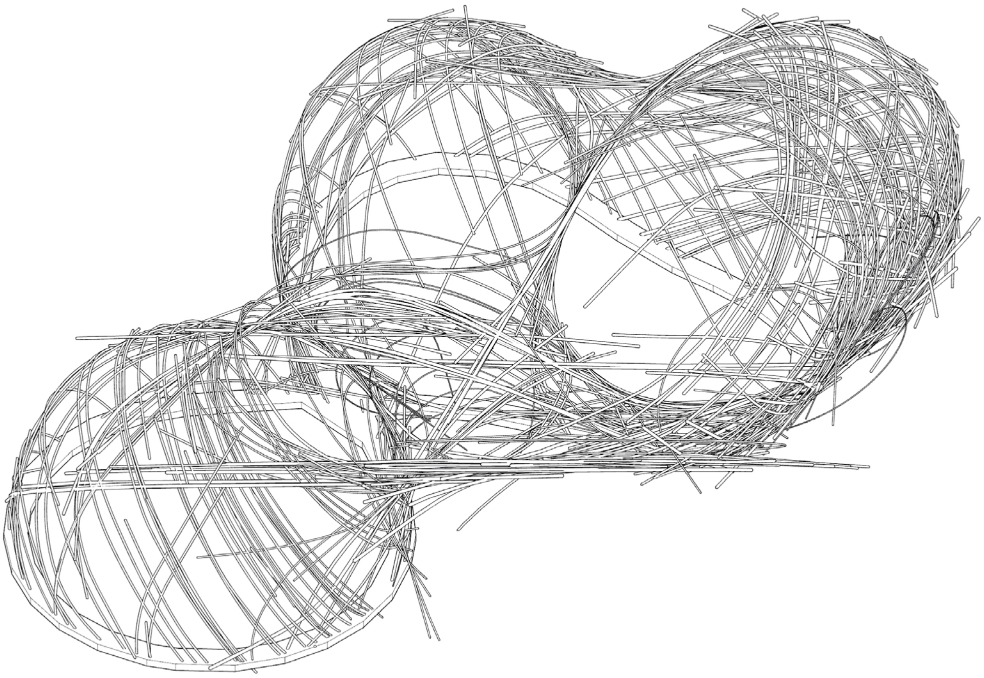
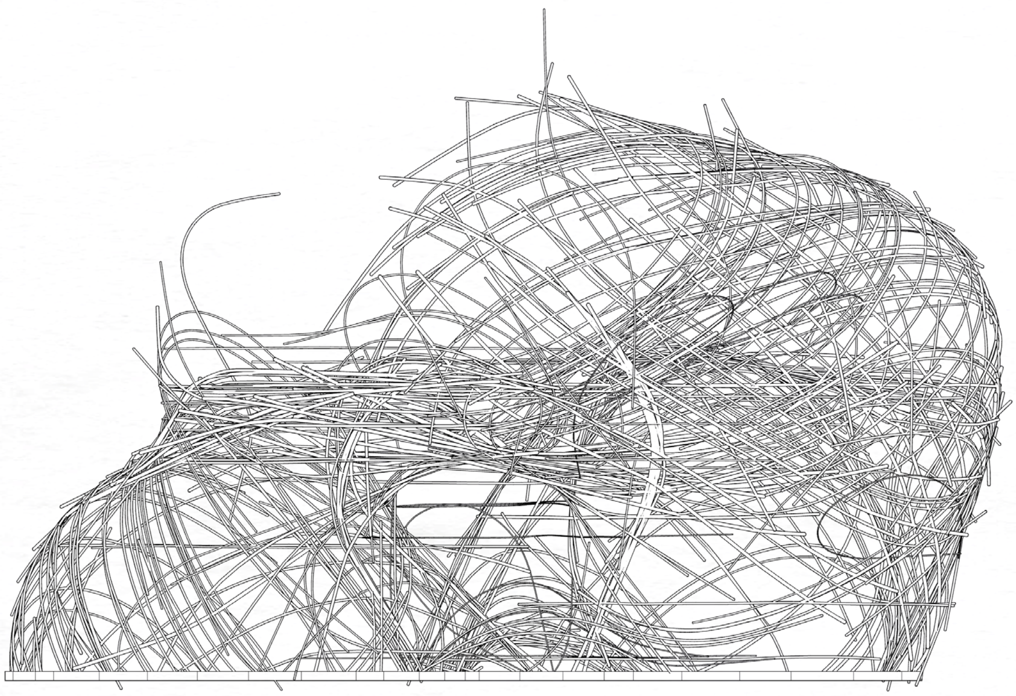


Figure 4: The Social Weavers Demonstrator (Bennetts 2013)





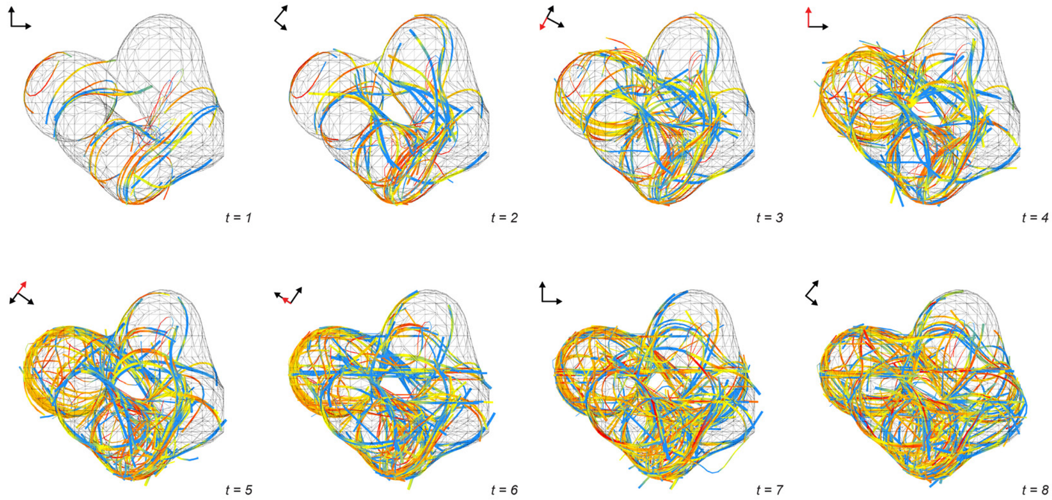


Figure 5: Elements are gradually introduced into the simulation, with differing orientations. The bending stresses experienced by each element are visualized throughout thesimulation, and impact upon the material specification of ach element (Nicholas 2013).

An alternative description of this dichotomy is provided in M.P. Schützenberger's classification of goal-seeking behaviours (Schützenberger 1954), in which he characterizes two similarly polar approaches to addressing a problem space as being strategic and tactical. In this context, strategic refers to the top-down, in that global algorithmic direction is produced through an exhaustive–and often complicated–examination of all possible solutions in search of the optimal. Effectively identifying an "ideal" instruction set for all component elements, it defines a final state according to a centralized intelligence. A tactical approach, then, reflects the bottom-up such that a series of localized algorithmic decisions are deployed in smaller spatial and temporal steps. This process discretizes–and seeks to simplify–the problem space into sets of localized conditions, which then may incrementally accumulate to produce movement toward the desired goal.

Interestingly, Schützenberger uses this general distinction between the strategic and the tactical as a framework to reconsider their perceived dichotomy not as isolated states, but instead as conceptual end-points along a continuous spectrum. To achieve this, he demonstrates each to be a derivative of a single mechanism, related to interpreting a solution for a problem space, with the distinguishing variable being the "span of foresight"–or the scope–used to discretize the deployment of the decision-making algorithm. This span of foresight becomes a measure to understand the tendencies of a model not in absolute terms, but rather as a gradient: larger scopes of decision result in more top-down decision systems, and smaller scopes of decision result in more bottom-up decision systems.

A general trend in computational design thinking has been to privilege bottom-up generative systems as being ideally suited for dealing with complex design concerns. These are also typically seen to exhibit emergent properties favorable for addressing dynamic or differentiated intrinsic and extrinsic conditions (Hensel et al 2010). Such systems might also be recognized as the "open-ended" design models that Peter Cariani considers necessary for addressing "ill-defined problems that defy direct solution" (Cariani 2008). In the context of this trend toward the bottom-up, however, the role of the designer in developing or managing a set of controls is less clearly defined, or is perhaps minimized in description in service of the epistemological framing of the emergent. And though it may be possible in theory for a model to be wholly bottom-up, in practice nearly all computational design models rely on some capacity of top-down approaches, even if only acknowledged as being involved in setting boundary conditions associated with generative algorithms, material specifications, or the array of assembly systems. Conversely, if a computational design model should be understood as producing new information about a design system–in contrast with a computerized model, which operates as a translational procedural representation (Terzidis 2006)–then in some capacity, a computational model must necessarily exhibit some type of bottom-up behaviour through interdependencies between component elements. Real-world design models are then operationally neither entirely top-down nor bottom-up, but instead are located along a continuum similar to that described by Schützenberger, with their constituent components executing instructions at different levels of spatial, temporal and informational discretization.

Through the lens of agency, this project recognizes simultaneous advantages in both approaches, and actively synthesizes the designer-control idealized in a top-down approach with the collective and emergent intelligence idealized in a bottom-up approach. Rather than privilege one over the other, it presents a design system that productively takes advantage of agencies associated across orientations: for the designer, the design space, the material, and the assembly. That is to say, at any particular level, a component of the model is informed in a top-down manner by other components, and produces new information via bottom-up processes that in turn become top-down specifications for lower levels of hierarchy.

6.3 Two opposed modes for agency-based modelling

Projects such the Faraday Pavilion (Nicholas et al. 2011) and Dermoid (Tamke

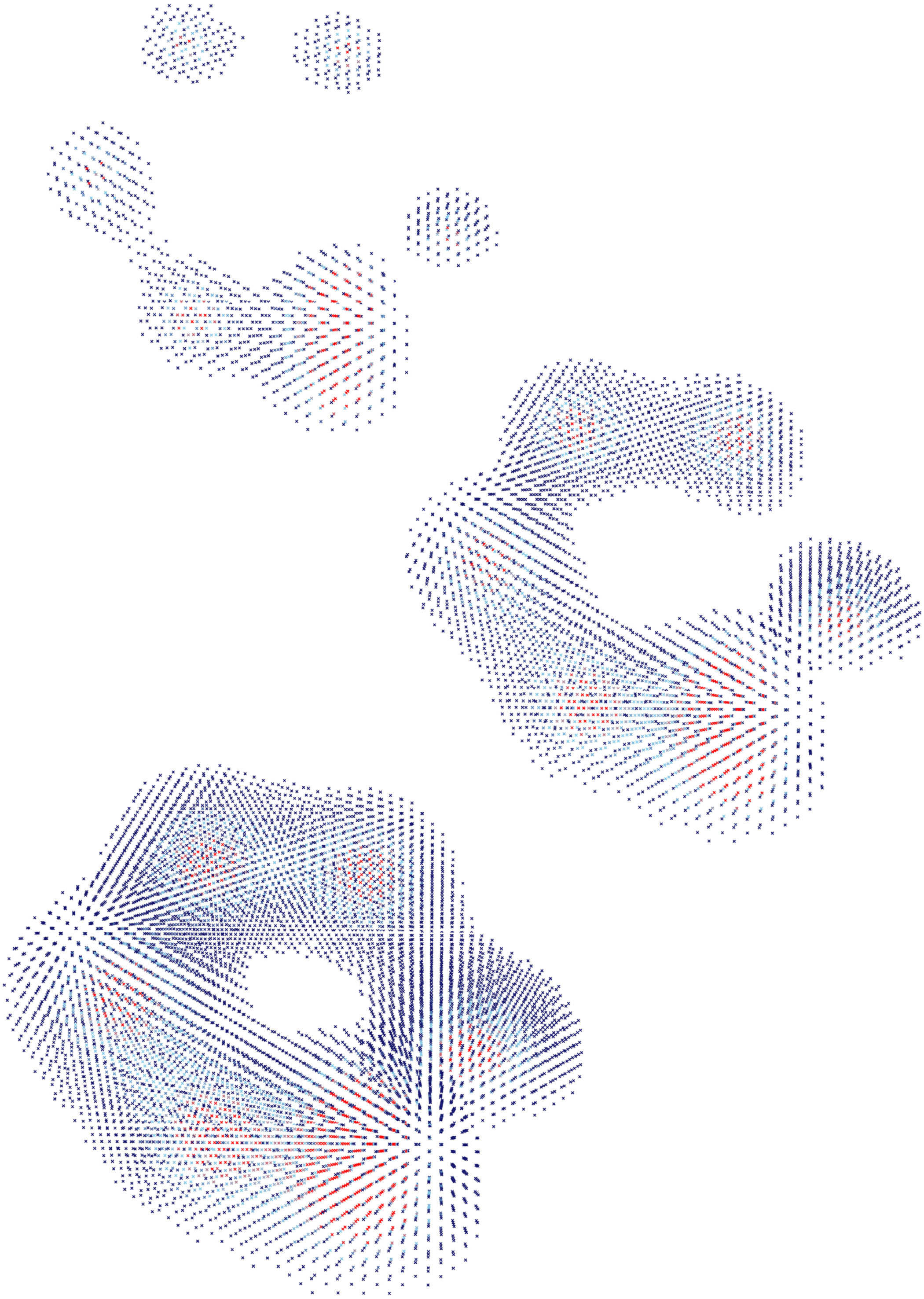


Figure 6: Standard particle-simulation forces used to model material behavior during morphogenesis: Hooke's Law spring force diagram, and Vector-normal bending force diagram (Stasiuk 2013).

et al. 2012) are characterized by the emergence of incremental intelligence through material agency, but also in the incorporation of an explicit design intent that is characterized by topological fixity.

Figure 7: (Opposite) Metaballs provide a dynamic design interface that can be adapted throughout the design process. Altering the threshold leads to significant changes in topology (Nicholas 2013).

The Faraday Pavilion gridshell uses bottom-up methods to approximate a pre-given geometry within the constraints of a specific material system: GFRP tubes. The project uses a lightweight physics-based design tool that incorporates the simulation of bending behaviour and the calculation of bending stress and material utilization. There are two stages of simulation: in the first, radial elements try to closely match a target geometry while remaining within their capacity for bending. As this first stage of simulation progresses, the geometric definition of each radial element emerges from the negotiation of the element's local utilization, its natural minimum energy bending behaviour, and the architectural design intention as captured by the target geometry. The second stage, in which transverse elements are introduced, is less directed. Transverse elements are constrained to the radical elements, but are free to change their start and end points as well as their path across the structure, which is influenced by material bending and length parameters. Lastly, the combined structural interaction of radial and transverse elements is simulated.

In the Dermoid, a base topology is developed from interconnected hexagonal polygons, and then affected by an interplay of forces, constraints and boundary

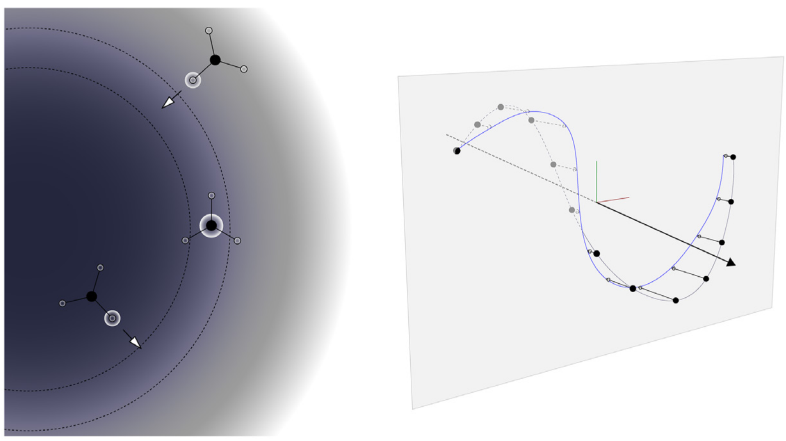


Figure 8: Metaballs provide a dynamic design interface that can be adapted throughout the design process. Altering the threshold leads to significant changes in topology (Nicholas 2013).

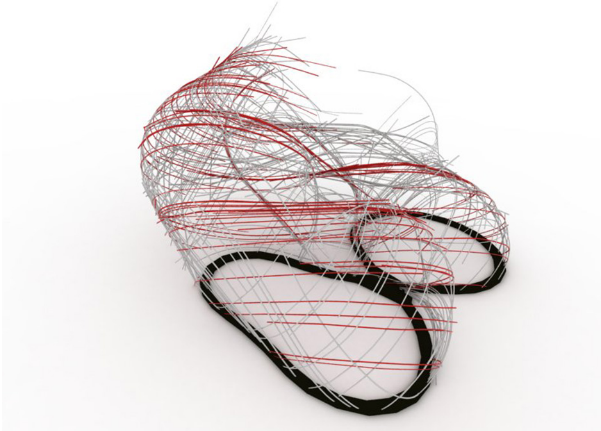


Figure 9: Highlighting a Single Orientation Plane within the Multidirectional, Layered Structure (Nicholas 2013)

conditions. A geometric understanding of the constraints, which are related to design topology, structure, material, and production and assembly, and their interdependency and relation to the overall system is established, and then resolved within a physics-based system. While the arch and dome-like shapes that emerge are not constrained in their number of edges or overlaps, the definition of polygons and their connectivity to one another can only be defined in advance of simulation.

The companion projects The Rise and the ACADIA Rise from 2013 reflect efforts to develop models that fully privilege open topologies, but do so at the expense of designer agency. The Rise was an installation piece shown at the Fondation EDF in Paris exhibit titled ALIVE–Designing with Living Systems. The ACADIA Rise was a second piece constructed as part of a workshop at the ACADIA 2013 conference, which extended certain key features of the generative system used in the Rise and explored alternative means of activating structural performance.

The primary generative algorithms used for these projects imitate vegetative

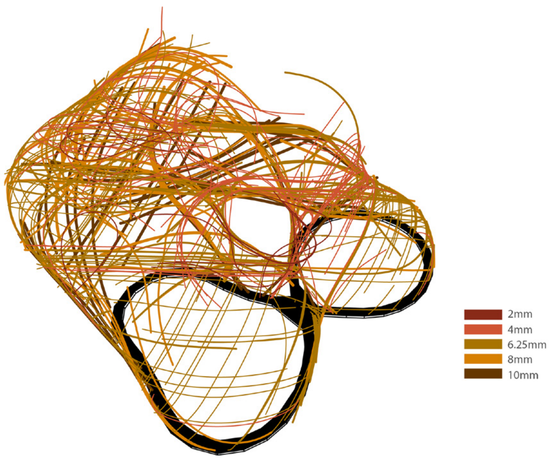


Figure 10: Material Differentiation as a Result of Simulation (Nicholas 2013)

growth, considering exposure to virtual sources of "light" as modes for catalyzing material accumulation through the step-wise passing of energy thresholds, with morphogenesis driven according to an algorithm notionally based on phototropism, the mechanism of growth towards light. Similarly, branching logics and material organizations respond to the model's "sensing" of local structural requirements. In order to fully activate the resulting material behaviours of the growth process, continuous particle-based simulations are executed as a critical component within the algorithm. In doing so, they collapse the cycle of generation, simulation and analysis into a series of continuously discretized and interdependent stages (Tamke et al 2013).

For each of these projects, the agencies produced through material simulation systems are essential for morphogenesis. The critical threshold that separates such modelling approaches–one tending towards the top-down, the other towards the bottom-up lies in the notion of topological fixity. For both the Faraday Pavilion and Dermoid, though they implement material agency through simulation, they nonetheless rely on complete designer control for the setup of each individual element, and all of the relationships between force elements. Conversely, the Rise and the ACADIA Rise–while also simulation material behaviours–implement a wholly generative system whose lack of fixed relationships privileges emergent agencies at the expense of ongoing designer control. These projects thus define the problem space for an approach that may deliberately synthesize agencies that have typically operated at odds with one another in computational design systems.

6.4 Case study: The Social Weavers

The design possibilities of this new approach were investigated and tested in a five-day experimental design and build workshop, entitled "The Social Weavers". The workshop aimed to introduce students to methods through which digital-material practices are able to introduce simulation and design data into the process of materialization. It used the design of pre-calibrated, bending active composite material assemblages as a mode of operation.

The workshop commenced with an introduction to materially informed design strategies and the concept of active-bending. Students were introduced to the computational design tool and undertook initial investigations to develop design schemes for the project site. In tandem, they conducted a series of experimental and empirical material tests to determine the minimum bending radius of each diameter composite rod, as well as young's modulus and bending strength, to calibrate the design tool. All schemes were presented to the teaching team and entire student cohort so as to identify and select advantageous aspects to be taken forward into a new design iteration. This process repeated until a final design was agreed. The students were then divided into small teams, which had responsibility for specific tasks, such as site preparation, production of the fabrication information for the guide work, labeling all member groups variously to prepare for the assembly of the nest.

The Social Weavers structure (Figure 7) and (Figure 8) is made from actively bent fibre composite rods of varying diameters. The non-standard grid shell structure is approximately four meters by four meters by three meters, and comprises 412 three-meter long rods. The initial design inspiration is found in nature, where birds such as the weaverbird weave structures from continuous grasses, one element at a time. The incremental addition of elements to build the nest allows for more complex topologies and forms to emerge. This incremental process also allows for a distinctly 'designedly' approach, in which material can be added, then considered, adjusted, and added to again. An extreme example is found in Southern Africa, where the Social Weaver (philetairus socius) builds large compound community nests. These are some of the most spectacular structures built by any bird.

The installation structure is based on the placement of more flexible material in areas of greater curvature, and stiffer material in flatter areas. This has the effect of minimizing reaction forces, and maximizing shape approximation. The structure uses five different diameter, glass reinforced rods: 55 are 10mm diameter, 116 are 8mm, 156 are 6mm, 70 are 4mm and 22 are 2mm. These diameters are the outcomes of the computational process.

6.5 Shaping the nest

The Social Weavers installation is conceptualized as a nest. It is comprised of multiple, actively bent splines that are articulated through a network of collected, interwoven elements, whose local behaviours aggregate into a globally non-linear structural assembly. The central component of the design model for the Social Weavers is the custom-written, verlet-integrated spring-based simulation library that is set up specifically to allow for collections of particles to be organized through unfixed and transitional topologies. It allows for the incremental addition of new elements over time, and for existing elements to continuously undergo reassessment of the force relationships in which they participate (Figure 5).

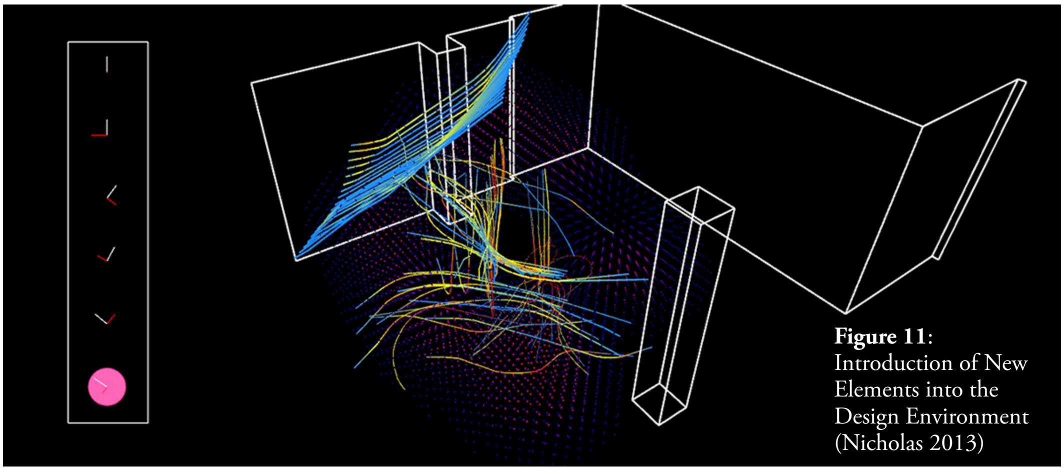


Figure 11: Introduction of New Elements into the Design Environment (Nicholas 2013)

For the simulation of the individual elements, forces that have been demonstrated to effectively describe the elastica-driven behaviour of elements operating in active bending are deployed (Ahlquist et al 2013). Each spline is subdivided into an appropriately-dimensioned subset of particles for defining both the springs which use Hooke's law for resolving elasticity in the long axis and the vector-normal method for resolving the forces applied for the description of elastic bending behaviours (Figure 6).

In addition to these "natural" forces which effectively describe environmental and material behaviours in the design model, the Social Weavers also relies on a series of "artificial" forces that empower the designer to more directly assert agency in a design process that relies on unfixed topologies that undergo continuous transformation during simulation (Figures 7) and (Figure 8). These forces create influence on the organization of the splines in multiple capacities:

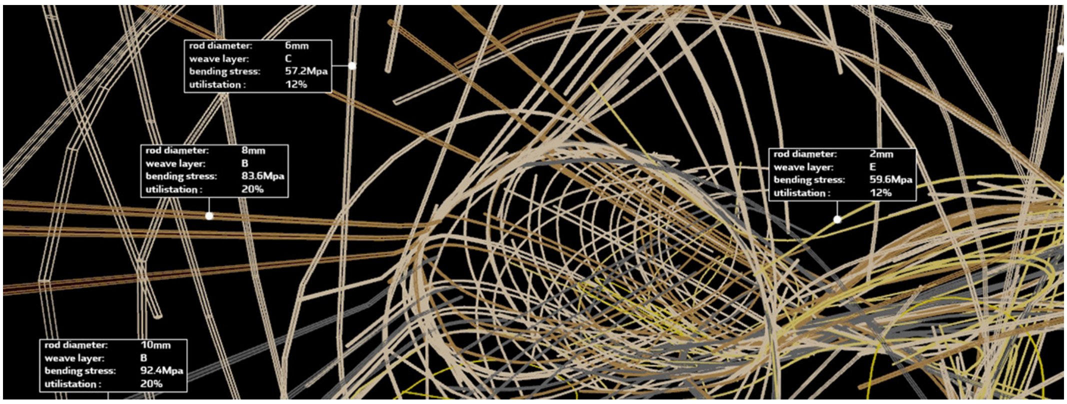
1. for movement along the gradient of a scalar field;
2. according to a series of planar orientations; and
3. as instruments for creating separation between splines that share these orientations.

Operation of the design model for the Social Weavers consists of establishing the parameters of the scalar field that will be used to shape the morphology of the assembly, determining a set of different weave orientations for arraying the actively bent splines in space, and finally, during the execution of the simulation, incrementally releasing splines elements into the design space and allowing them to self-organize within the designer-set parameters. At any time during this modelling phase, the designer is capable of making adjustments to any of these forces, effectively reorienting elements or adjusting the underlying scalar field that drives the general organization of individual elements.

Unlike many nests that are designed for smaller units of birds, the geometric variation of the Social Weavers is an expression of the multiple distinct spatial conditions required of the complex social organizations emblematic of the nests of the birds after which the installation takes its name. For the design model, this diagram for growth is interpreted by considering morphogenesis as a response to a scalar field condition. In order to achieve local differentiation, this field is defined using a metaball falloff function with multiple centroids, and any number of points and associated radii, together with a threshold value, can be used as inputs for the centroids. Their number can be increased or decreased at any time during the simulation, and the threshold can also be adjusted, making significant topological change possible.

The scalar field force applied for the Social Weavers contrasts with forces in many simulation engines that rely on target geometries for either pulling or repelling particles. In these latter instances, forces typically rely on closest point calculations to determine the vector of influence on a given particle, movement that is purely normal to the target geometry. For the scalar field sample gradient force, however, each particle continuously samples itself within the field being evaluated. Each particle then senses the space around itself and determines the vector that indicates the optimal direction for movement towards the designer-defined ideal field threshold. With metaball fields, this then does not necessarily result in movement toward the normal of the surface condition, but can in fact reflect movement along the isosurface interior, or between apparent ideals. The process of sampling this field for each particle rather than pulling it to a design mesh–fixed or unfixed–then allows for the actively-bent splines to engage in a more nuanced force-based relationship with the design environment as it reflects a direct dialogue between design

Figure 12: Differentiation of Material Specification as an Outcome of the Simulation (Nicholas 2013)



and material agencies.

The second, related control for this designer-driven approach is an orienting force. In order to ensure the proper densities of fibres across different directions, this orienting force is devised to allow for the designer to specify a collection of ideal, cross-laminating orienting planar coordinate systems that are assigned to different groups of fibres such that each first establishes an origin for itself in Euclidean space–at a point that averages its particle locations–and the target coordinate system is copied to this origin. Then, relative to their own locations in space, the constituent particles are drawn into this alignment. This keeps multiple fibres assigned to the same orienting planes parallel to each other, but free otherwise to move throughout the design space (Figure 9). This force is closely coupled with a simple separating force, such that fibres that share the same orienting plane are repelled from one another up to a cutoff length. This prevents the fibres from overly bunching in areas along the scalar field that reflect the highest degrees of relaxation.

Finally, the simulation supplies the parameters for a dynamic system for material specification. The relaxation of the elements is affected by multiple forces as described above, which require the element to be either straighter or more curved. Each element begins with a 10mm diameter specification, which changes as the element encounters differing conditions. Change in diameter is driven by utilization, as a function of bending stress, which is recalculated during each iteration. If an element of a particular diameter is utilized by greater than 70 per cent, meaning that it needs to negotiate higher curvature, it reduces its diameter by one step. If an element is utilized by less than 30 per cent, meaning that it is straighter, that element increases its diameter by one step. The diameter steps are 2, 4, 6.25, 8 and 10mm (Figure 10).

6.6 Designer agency

The Social Weavers relies first on the designer definition of the metaball centers and charge values, and secondly on the incremental introduction of sets of splines into the modelling environment. The design space enables the designer to visually rotate collections of splines around the target metaball field and release collections of splines toward it–to do so, the designer defines an orientating plane, the number of elements and their length, and the position from which those elements will be initialized in the simulation (Figure 11). Because each collection of fibres introduced into the modelling environment is assigned a particular orienting plane, through the layering up of multiple elements over multiple orienting planes, the designer is able to ensure that the fibrous coverage of the metaball field condition is evenly distributed in cross-laminated patterns. A multi-directional structure then is gradually established over the target field, the time-dependent nature of which allows for the designer to get immediate feedback regarding both performance and organization. The final path, position and material specification (Figure 12) of each element then is influenced by a collection of tactical forces that describe movement along the scalar field gradient, attraction to locally-originated orienting planes, a desired minimum spacing from elements with the same orientation, and by the element's underlying elastic behaviour. Most significantly, however, all of these bottom-up force calculations and unfixed topologies are directly supervised strategically by the designer. The assertion of designer agency is embedded such that the advantages of an emergent, locally responding design system can be deployed with a high degree of intentionality and control.

6.7 Discussion and conclusion

The Social Weavers demonstrates the application of such an approach to encoding and deploying material behaviour, specifically the bending and directionality of GFRP rods. The project seeks to capitalize on the simultaneous deployment of multiple agencies in the design environment, specifically the agency of the design-er, the agency of the design space, and the agency of the assembly. While it has supported a more designedly approach to defining materially informed and emergent, non-standard gridshells, the modelling that underlies the project is currently limited, in that its structural simulation fails to take some key considerations into place, such as the effect of connections between splines and global performances. The reason for this exclusion is computational cost. While the scale of the physical demonstrator allows this freedom, in order for this approach to be scaled up, it is important that this aspect be addressed. This paper argues that top-down and bottom-up processes should be thought of as a continuum, rather than as two opposed poles. That is to say, at any particular level, components of a model might be informed in a top-down manner by other components, and produce new information via bottom-up processes that in turn becomes top-down specifications for lower levels of hierarchy. Such a view affords new approaches to the inclusion of agency within design, and the opportunity to extend upon existing design models by incorporating and synthesizing explicit design intent, the emergence of intelligence through material agency, and open topologies. The need for synthesis between bottom-up and top-down approaches is driven by architecture's increasing involvement in the design of programmed relationships between matter and energy, and the designed orchestration of material formations such as The Social Weavers installation. This material practice requires more than solely top-down or bottom-up approaches in which agency too often appears a zero sum game, where its granting in one aspect must reduce its deployment in others.

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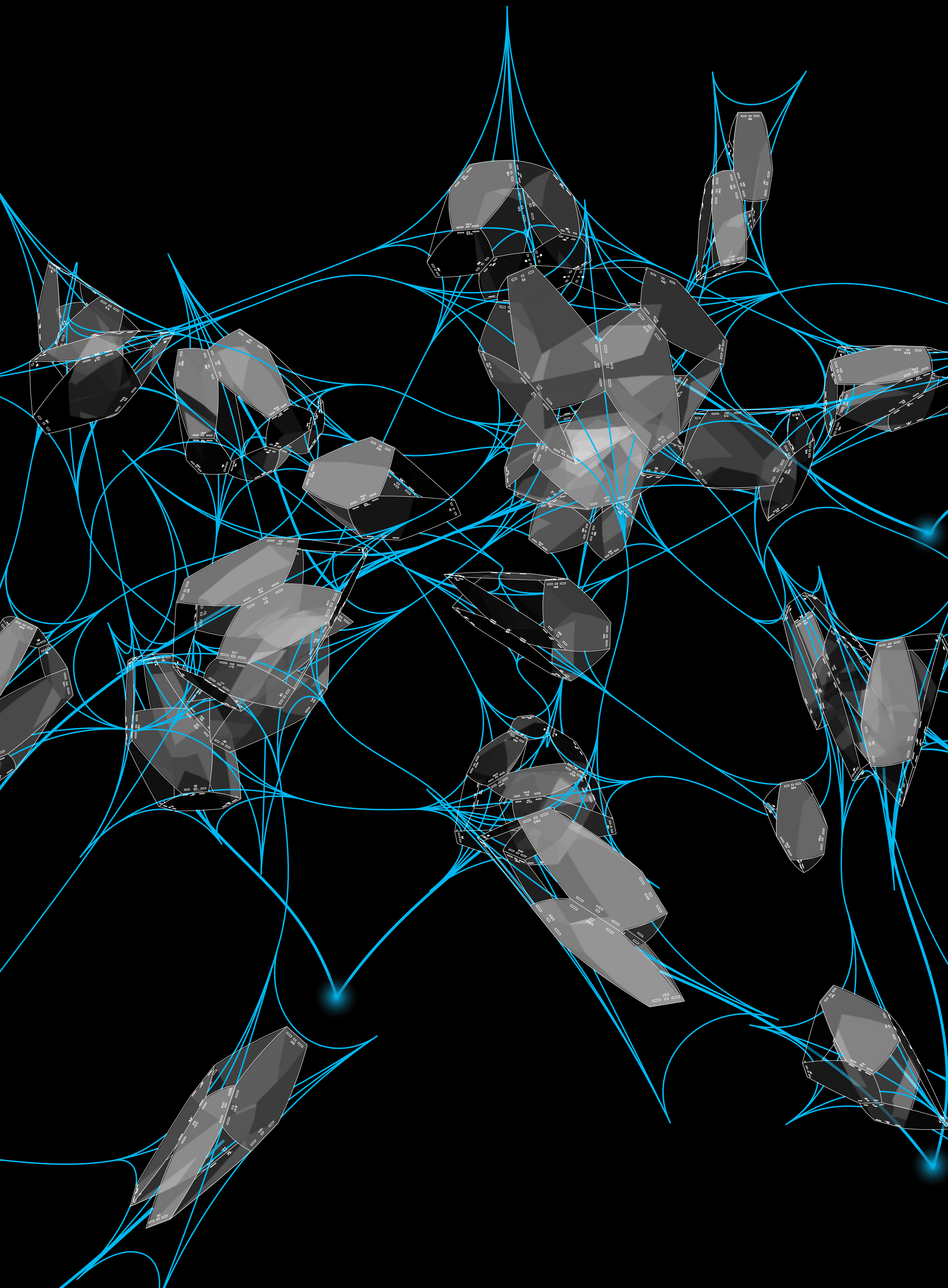
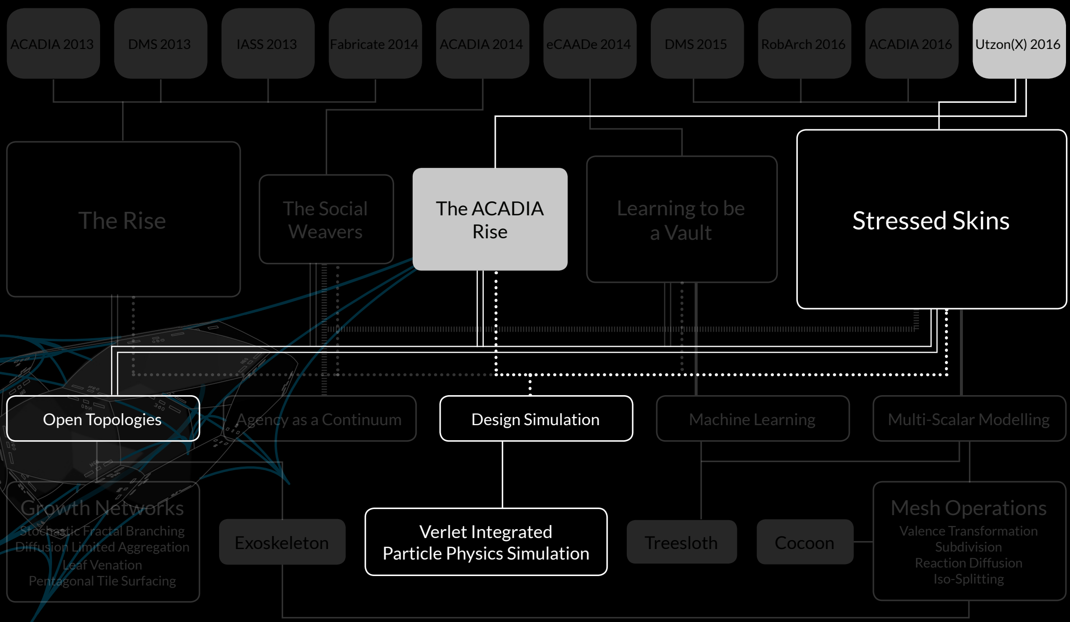




Publications III: Digital Simulation

The fourth publication presented here specifically engages in digital simulation as its primary topic and synthesises many of the findings and approaches reflected in the experiments through which this research project was pursued. This is a peer-reviewed book chapter from Bricks/Systems and was written pursuant to my participation in the Utzon(X) Summer School course held in the 2014 at the Aalborg University, Department of Architecture, Design and Media Technology.

> Stasiuk, D., & Thomsen, M. R. (2016). *Digital Simulation for Design Computation in Architecture*. Bricks/Systems, 83. Aalborg, Denmark: Aalborg University Press.

Engaging with Design Simulation and Open Topologies

Each of the experimental projects presented as central to this research project features the use of design simulation as a critical component to the modelling framework. As the previously presented papers on *The Rise* and *The Social Weavers* demonstrate, simulation systems behave as frameworks for more direct and effective means to implement dynamic feedback loops. These projects use the simulation of material behaviours to collapse the cycle of generative form-making and analysis into a more tightly integrated representational engine. They achieve this through the use of custom data structures that are formulated to manage the open topologies that generative design systems are realised through, such that through simulation of the design system, processes of adaptive parameterisation are initiated, where the feature space that exists between discrete modelling systems becomes dynamically activated and changeable based on continuous feedback.

The book chapter presented here examines the role of simulation for different experimental projects – looking at the built projects *The ACADIA Rise* and *Stressed Skins*, as well as the speculative *Utzon(X) Masonry Pavilion*. Importantly, it does this to more deeply explore explore computer simulation as a topic of epistemological interest, exploring differences and similarities in its role for both the natural sciences and design disciplines, with an especial focus on the latter. It presents a framework for considering how the application of simulation specifically within a design context can stimulate processes of invention and discovery, imbuing design models with the capacity to increase designer intelligence about target systems of interest that either constitute or interact with the designed artefact or its digital model.

Project role

For each of the projects presented in this paper, I was the principal or exclusive developer of the modelling systems used for their design

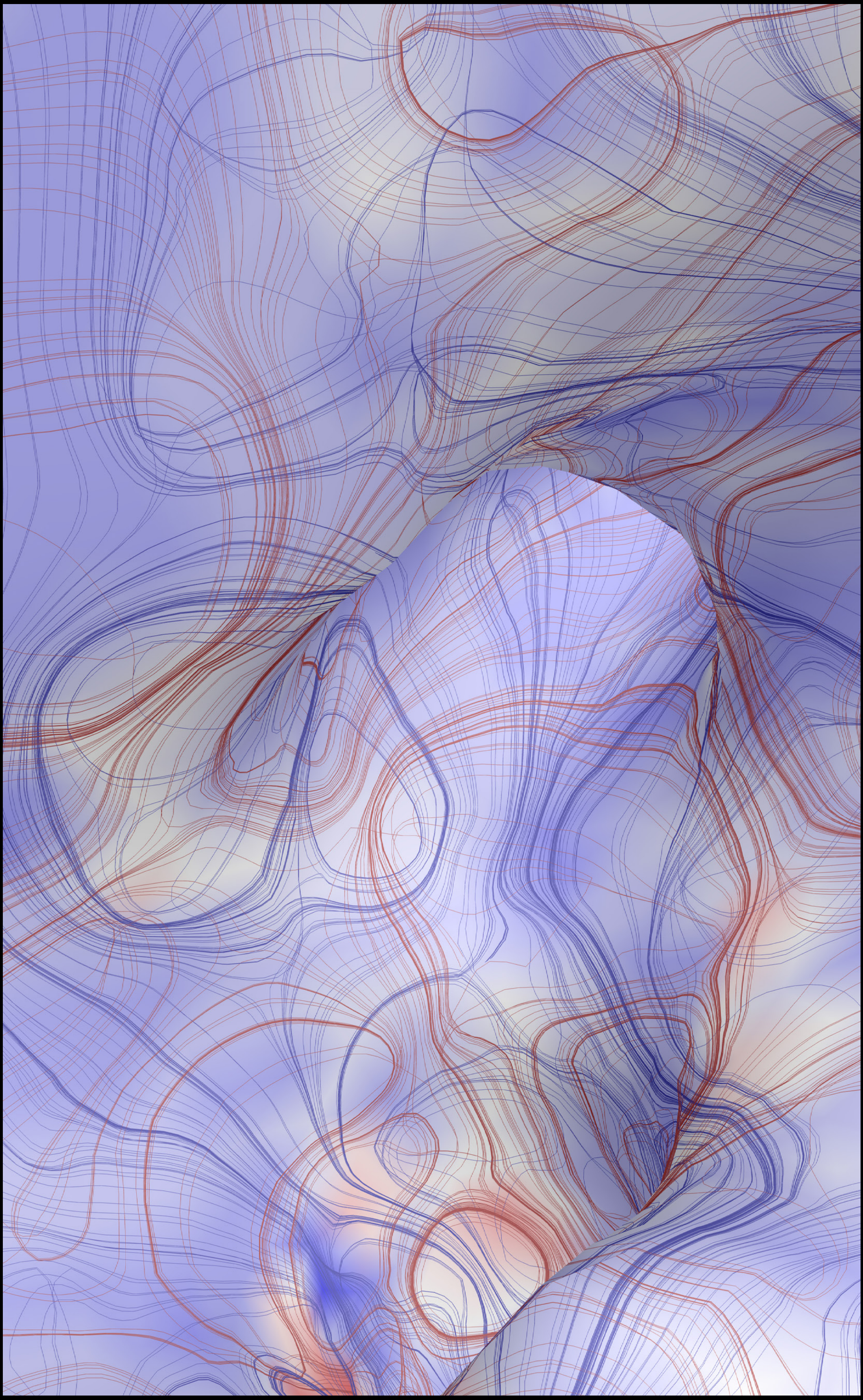
Author role

As the primary author for this publication, I contributed all of the text, responding to feedback provided by my thesis advisor and co-author, Mette Ramsgaard Thomsen.

Presentation

The papers presented here have been reformatted for continuity, but all textual and visual content remains unaltered from its original, peer-reviewed presentation.

Figure: (Opposite) From a finite element analysis simulation, a visualisation of principal lines of stress on a doubly curved surface for early-stage digital design probe for the *Stressed Skins* experimental project.



7. Digital simulation for design computation in architecture

Reformatted from: Stasiuk, D., & Thomsen, M. R. (2016). *Digital Simulation for Design Computation in Architecture*. Bricks/Systems, 83. Aalborg, Denmark: Aalborg University Press.

Abstract

Architectural practices that employ design computation in their work flow rely on digital simulations of many types to instrumentalise both projective analysis and generative form-making. In the context of design-led research, this paper reflects on simulation in architectural design, contextualised through a brief examination of its application in the natural sciences and engineering. It examines critical similarities and differences in both theory and practical deployment across these different types of practice, looking to historical ideas and markers to broadly frame these qualities, especially to discuss the varying degrees of maturation and fidelity simulation exhibits in these fields. It then examines three architectural design projects as case studies for the exploration of these ideas as they relate to design-led architectural research practices. The aim is to outline an approach for designers to develop strategies for the validation and verification for their simulations. The argument made here is that the primary goals for architectural designers deploying simulation is to continuously aim toward higher-fidelity results while simultaneously

prioritising a degree of flexibility that enables the assertion of authorship in service of design goals and parameters that lie outside the purview of the simulation. It is in the resolution of these two sometimes competing interests that the architectural designer pursues an ideal approach: that simulation may enhance processes of invention and discovery even as it supplies actionable feedback for target behavioural and performance features represented in the design model.

7.1 Introduction

Digital simulation is currently used for architectural design in a broad range of both design-led research and professional practices for a wide variety of functions. Among other applications, simulations of different types are capable of representing material behaviours in structural assemblies (Tamke, Stasiuk, and Thomsen 2013), of directing form-finding operations(Kilian and Ochsendorf 2005), and of illustrating the impact of geometric organisation and material assembly on environmental considerations in relation to lighting (Ward 1994), thermal performances (Larsen, Foged, and Jensen 2014) and fluid dynamics analyses (Bartak et al. 2002). It has been extended into predicting patterns of occupancy across multiple scales, from the individual inhabitant (Shen, Shen, and Sun 2012) to urban-scale circulation flows (Farenc et al. 1999). Some architects assert simulation-based techniques beyond efforts to describe "real" systems and deploy them through generative tools, where they are used to activate agent-based design systems or algorithmic constraints whose rules are formally-driven or highly abstracted (Nicholas, Stasiuk, and Schork 2014). Despite these advances – and of course with certain exceptions – the application of digital simulation in architectural design in crucial ways lacks the maturity of methodology and instrumental sophistication available to simulationists in the natural sciences and engineering[1]. This apparent disparity in the application of simulation in architectural design versus the harder sciences seems due to a number of important factors related not only to the history of simulation and computation, but also to key epistemological differences between design disciplines and the sciences. This paper reflects on

1 Frequent references will be made in this paper to the "natural sciences and engineering." The breadth of these fields is recognised, as is the necessary compression made in any characteristic statement about them. Any reference made to these groups in relation to their deployment of simulation therefore focuses almost entirely on tendencies and is certain to contain both exceptions and omissions. Furthermore, the decision to locate engineering with the sciences rather than with design disciplines is recognised as contentious. It is based here on a primary assertion that engineering is more generally an "applied science" that is concerned with well-defined problems that have clearly discernible boundaries for evaluation.

those qualities in purpose, model construction, and evaluation that distinguish design simulation from scientific simulation.

7.1.1 Paper structure & background

This paper will be organised in four sections. After the introduction, the second section will briefly contextualise simulation as a design concern relative to the field of architecture's own traditions of representation as well as to simulation as it pertains to the natural sciences and engineering. It will also outline the argumentation for understanding differentiated epistemologies for design simulation versus scientific simulation. The third section uses a series of three case studies that provide an exploratory framework on this topic through an interrogation of difference in each project's application of simulation techniques, with a specific focus on meterial behaviour, structural performance, and interactive form-finding. The final section of the paper will collate the findings from these experiments in a reflective discussion about simulation for design computation in architecture. The research for this paper is produced for the 2014 Utzon(X) Summer School, and is a component of David Stasiuk's PhD research within the "Complex Modelling" framework at the Centre for Information Technology and Architecture (CITA). This project is a Sapere Aude Advanced Grant research project supported by The Danish Council for Independent Research (DFF). The grant was awarded to Mette Ramsgaard Thomsen. The project started in September 2013 and will run to August 2017.

7.2 Simulation frameworks

Since the advent of the computer in the middle part of the 20th century, digital simulation has played an increasingly important – even essential – role in the study of the natural sciences and in engineering research and practice, fostering entirely new approaches for hypothesis development and testing, and enabling new experimental methodologies. In broad terms, scientists use digital simulation as a proxy for physical experimentation. Through it they test existing theories, investigate new frontiers, and make predictions regarding the behaviours of attendant or integral complex systems. Engineers use simulation not only to calibrate and optimise well-understood assemblies such that they can produce solutions they are confident will meet performance criteria, but also as experimental platforms to develop and to test new strategies for continuously extending their capacities to produce such measurements into new territories of knowledge.

Soon after the construction of the earliest digital computers in the 1940's, researchers and computer scientists sought to both develop digital frameworks and formalise general approaches for modelling and simulation that could be applicable over multiple topics of inquiry. By 1960, a specific field for modelling and simulation (or "M&S") had emerged, with its own rapidly evolving methodologies and epistemology (Nance and Sargent 2002). This rapid specialisation by a subset of computer scientists toward the development of modelling approaches idealised for their application over any type of system belies the fact that the very earliest digital computers – such as the British Colossus and the American ENIAC – were often developed with specific calculations to be performed in mind. The visionaries who designed them came from a variety of fields, and were exploring computation in order to create tools for themselves such that they could model, investigate, and systematically calculate on unprecedented scales highly domain specific functions. Of course, people like Alan Turing had an intense interest in and were highly motivated by more generalised computational theory. For example, Turing's own famous work on the "Entscheidungsproblem" is one of many that delves deeply into computational abstraction and is motivated by the more purely mathematical (Turing 1937). And indeed his and his contemporary's work was built upon foundations set by even earlier visionaries, such as Charles Babbage, Ada Lovelace, George Boole and John Venn (Bullock 2008). But Turing also was deeply interested in computational development for specific and applied purposes, famously for code breaking during World War II and later in the deployment of algorithms that could describe complex and emergent behaviours seen in chemical reactions and natural patterning (Lepp 2004). John Von Neumann's contributions to computational development were at least as vigorous and vital, and even more directly tied to the pursuit of applied research in a massive diversity of fields, especially military interests and nuclear physics (Eckhardt 1987). These earliest developments in digital instrumentation during the middle part of the 20th century were the product of an ongoing objective for digital computation to provide mechanisms suitable for modelling, describing and predicting the behaviours of target systems. Fundamentally, the early visionaries were developing these engines to perform simulations, and the communities that emerged around computation in these early years reflect this polyglot approach. It was then only after simulation was deployed in direct application that it formally emerged as a topic of interest in itself. Its history in science and engineering is then front-loaded with practice-oriented interests first and foremost, its contemporary formulation into a neutral framework pursuant to its functional use.

As is natural in the evolution of any field of study and its epistemology, since the advent of M&S as an independent field the term "simulation" has accumulated a varity of occasionally contradictory definitions. For this paper, simulation will be defined as "the process of developing a simplified model of a complex system and using the model to analyze and predict the behaviour of the original system." (Ören 2011) In practice, simulations rely on the process of describing sequences of changing states for the target system under inquiry. They iteratively use the information encoded consecutive states to develop their predictive calculations for the next. For the scope of the discussion here, the interest lies specifically in *continuous simulation models*[2] that produce actionable information through iterative computation.

7.2.1 Analogue simulation in architecture

Prior to the formalisation of M&S practices starting in the 1950's, functionally-driven, simulation-based practices had already taken purchase through analogue media in a variety of fields. Interestingly, architectural design has a rich and well-documented history in this vein. In the field of architectural design, then, the types of continuous simulation practices pertinent to the argumentation of this paper exist along two trajectories. These can be differentiated both historically and according to relevant media, with the first comprised of analogue simulation approaches for architectural form-finding, and the second reflecting the translation of these practices into a digital environment.

Early analogue simulation practices in design are directly related to the dynamic form-finding of structural systems, largely by master-builder architects or engineers. Their origin can be located in Robert Hooke's work demonstrating the structural performances associated with the catenary arch in the latter half of the 17th century, and their maturation traced through the 19th century with the formalisation and mastery of graphic statics (Allen and Zalewski 1996). For many of the early practitioners of these techniques, these tools were used to calculate or reflect upon designs that had already been asserted from the top down. But starting with Antoni Gaudi in the very last part of the 19th and early parts of the 20th century, these methods were extended in the creation of dynamic form-finding "designing machines" (Huerta 2006). Gaudi is of course famous for his hanging chain models that extended 2D representations of

2 As opposed to state sequencing or discrete event models, continuous simulation models represent "state changes as continuous over time, and discretized approximate solutions of differential equations are the most common examples." (Nance and Sargent 2002)

catenary networks into complex 3D vaults, as in his work for the church of the Colonia Guell. But he also worked extensively using graphic statics approaches specifically as a generative drawing tool for form-making, as did such other engineering visionaries as Robert Maillart and, later in the 20th century, Pier Luigi Nervi. Heinz Isler also worked through analogue simulations of shells through hanging textiles. The primary contributions made by these and others is tied to the types of form-finding they were able to derive from analogue drawing and modelling practices, especially in regards to the discretisation and simplification of complex material and structural performances into tractable, design-oriented systems.

For these practitioners, despite the maturity of their approaches toward analogue computation, there was little explicit notion that they were performing "simulations" as defined here. Of course, a great deal of their work preceded serious developments in applied digital M&S. And indeed, even following the advent of digital computation, the sophistication specifically related to form-making available through analogue techniques vastly outstripped any capacities afforded by newer digital simulation tools which – attended by a series of important developments in finite element modelling, especially in the 1950's and 1960's (Thomee 2001)– first emerged as evaluative rather than generative instruments. This apparent discrepancy between computational applicability toward form-making between the analogue and the digital is exemplified in the practice of Frei Otto at the ITKE. In important ways, his body of work represents both the apotheosis of analogue simulation and its hinge toward a digital practice, as his practice increasingly relied upon the analytical capacities afforded by digital computation even as they continued to push the computational power of material assemblies through rich and disciplined form-finding investigations.

7.2.2 Simulation in the natural and artificial sciences

The maturation of M&S has run lock-step with advancements in electrical engineering and computer science practices – over the second half of the 20th century and now well into the 21st – and is marked by an attendant expansion of knowledge in multiple directions. It has grown broader in the sense that fundamental tools have become more powerful in terms of computational capacity and flexibility of application, and approaches have become codified for general application independent of topic. And it has grown deeper in the sense that highly focused, domain-specific applications are developed for modelling complex, individualistic systems within discrete fields of research and practice (Nance and Sargent 2002). Finally, these technical and methodological developments have been tracked through an emerging epistemology of simulation, especially as it pertains to practice in the sciences, engineering, and design disciplines (Winsberg 1999).

Two key operations in building and testing a simulation model are validation and verification. In "Science in the age of computer simulation," Eric Winsberg focuses on these operations not only for their functional purpose but also as the key concepts in an epistemology of simulation. In simplest and most ideal terms, validation refers to a model's internal consistency in construction and correctness in executing its constituent methods of calculation, and verification refers to a simulation's capacity to correctly describe or predict the behaviour of the system it is modelling. However:

> *The epistemology of simulation does not divide as cleanly into verification and validation as this picture suggests. I would argue, that is, that simulationists are rarely in the position of being able to establish that their results bear some mathematical relationship to an antecedently chosen and theoretically defensible model. And they are also rarely in a position to give grounds that are independent of the results of their 'solving' methods for the models they eventually end up using.*

Here Winsberg points out that, ideal practices aside, developing simulations can be a messy enterprise. In fact, he spends a considerable portion of time outlining how simulation construction is akin to sausage-making: it is often a mash-up of multiple theoretical bases that require complex handshaking algorithms and are accompanied by stabilising "fictions" that lie outside the purview of theory and simply act as numerical instruments for maintaining order in a model. Yet regardless of the ambiguity this functional heterogeneity introduces to simulation modelling, processes of validation and verification must ultimately sanction only those models whose direct fidelity to the systems they aspire to describe are observable in practice.

With all of this in mind, Winsberg ultimately asserts that simulations are situated somewhere outside of both theory and experimentation, and represent a new and critical mode for developing an understanding of target systems, and for predicting their behaviours in projective environments. But his interest is also primarily in the sciences and those aspects of engineering where knowledge production, system and theory testing, and predictive analysis are the dominant goals for practice. How these ideas fold into an epistemology for simulation in the design disciplines – and here specifically architectural design – opens up new avenues for discussion (Winsberg 2010). In "The Sciences of the Artificial," Herbert Simon distinguishes design as "artificial science" in contrast to the "natural sciences:"

> *The natural sciences are concerned with how things are. Ordinary systems of logic the standard propositional and predicate calculi, say serve these sciences well. Since the concern of standard logic is with declarative statements, it is well suited for assertions about the world and for inferences from those assertions. Design, on the other hand, is concerned with how things ought to be, with devising artifacts to attain goals.*

Simon continues to describe that the sciences are necessarily driven through a process of deductive reasoning, and that while design processes that are clearly defined and open to optimisation are also open to these types of logics, at least as often design is concerned with problems that may not be fully optimised. And indeed, architectural design relies on parameters that are well-documented as being inherently broad in scope, varied in type, and often self-contradictory in nature. Architecture is therefore particularly prone to the "wicked problems" endemic to design disciplines that "elude reduction" (Buchanan 1992). This complexity is of a fundamentally different nature than the types of complexity simulationists seek to unravel through the modelling of systems in the natural sciences and engineering, which in many cases are more directly measurable. Simon would suggest that it allows for a move from deductive to inductive reasoning to find solutions that are good, if not optimised, an affordance he terms "satisficing" (Simon 1996)).

7.2.3 Digital simulation in architecture

Certain observers suggest that the emergence of simulation in architectural design is in fact simply attendant to the deployment and adoption of computerised tools – first through CAD, and then BIM – and as such by the end of the 20th century were already deeply embedded in most architectural practices (Loukissas 2008; Turkle et al. 2009). Shelly Turkle, for example, sees a designer spinning a 3D CAD model on a computer screen or producing a rendering of a digital model as working through simulation. This inclusive characterisation of representational practices as modes of simulation makes sense in the context of her larger argument about the sea-changes in both the design and scientific communities that have come through the often chaotic transition from primarily analogue to primarily digitally-based practices. But in key ways it contrasts with the argument made here, which takes the position that simulations operate in ways that are fundamentally different from pure visual and even spatial representations, regardless of their resolution or enhanced sensual tactility. The argument runs somewhat parallel to the idea that "computerised" design practice does not necessarily embody a "computational" design approach. In such a distinction, computational approaches enact key transformations to input parameters in the creation of new information about the design system, while computerised approaches need only operate in a digital platform, translating instructions without necessarily providing additive feedback. Even a complex 3D model can be "hand-drawn" – or computerised – in a CAD system: perhaps visually dynamic, but inert as an intrinsic generator of new information. As such, it operates as a receptacle for a design decision that has already been made.

As discussed, analogue simulation techniques for form-finding in architectural and structural design significantly pre-date the advent of the digital computer. Yet in contrast to modes of simulation for the natural sciences and engineering that paralleled the advancement of computer science from its origins through today, the development and adoption of similar form-finding architectural modelling techniques through digital instrumentation have only relatively recently emerged[3], firmly established by Axel Kilian and John Ochsendorf's 2005 paper "Particle-spring systems for structural form finding." This paper presents a methodology specifically oriented toward the digital production of a funicular modelling environment that digitises the analogue hanging-chain material computational strategy Gaudi employed for those complex vaults developed through catenary networks. Borrowing from developments and digital tooling well established in computer graphics and animation, the authors detail a methodological breakthrough that frames simulation specifically for form-finding these idealized structures (Kilian and Ochsendorf 2005).

Critical to the relevance of these techniques are two dependencies. First is the affordance they provide for architectural designers to rapidly develop open-ended digital design tools to experiment with form-finding observations that are endowed with plausible representations of material behaviours and structural performances. Secondly, they enable a parametrically controlled sculptural flexibility which empowers designers to assert authorship – often

3 Other forms of simulation – particularly those related to environmental analysis – somewhat preceded the current practices of physics-based form-finding. However, in practice, until more recently their application tended less toward a dynamic form-finding enterprise, and more in service of an iterative/analytical approach.

in ways contradictory to what a materially "optimised" approach would produce – in pursuit of those aspects of invention and discovery that produce inductive and integrated responses to "wicked" design problems. The particle-spring systems introduced by Kilian and Ochsendorf as architectural design instruments exemplify such an approach. And model validation in this context is derived from understanding the simulation schema for their basic connection to the underlying mathematics of Newtonian physics, to their historical precedence in computer science and engineering, and further as rooted in the earlier analogue simulations described above. But as such approaches become increasingly adopted, they have been extended through a number of alternate proposals and projects that introduce and examine less easily validated modelling setups. Physics simulations are frequently integrated with multi-agent systems that rely on designed forces to assert further authorship over design environments, optimisation instruments that press form into arrangements more suitable for fabrication, and other modes of performance evaluation. The validations of such hybrid models becomes perhaps more ambiguous and less deductive. And the question of their verification remains even more open. How are such models evaluated? How can design simulation that is guided by induction be sanctioned?

7.3 Case studies for design simulation modelling

This section begins to frame these questions through design-led research, focusing on simulation strategies deployed for three different projects. The first is The ACADIA Rise, an installation realised through a design/build workshop led by CITA during the 2013 ACADIA conference at the Waterloo School of Architecture in Cambridge, Ontario. The second project refers to the design model for the Utzon(X) Masonry Pavilion, which is developed during the 2014 Utzon(X) Summer School program held at the Department of Architecture and Media Technology, Aalborg University. The third project discussed is the Stressed Skins installation developed by CITA for exhibition at the Danish Design Museum in Copenhagen in the Spring of 2015.

Each of these case studies focuses on its own distinctive computational modelling approach in the application of digital simulation techniques for an integrated design system[4]. For discussion, both similarities and differences are

4 Unless otherwise specified, the digital modelling environment used for each of these projects is the CAD system Rhinoceros3D and its visual scripting plug-in Grasshopper (Rhino+GH). Grasshopper is operated through a directed, acyclic graph user interface that accommodates a variety of built-in components for instantiating

highlighted in order to provide a framework for understanding how strategies in model construction for design simulation can be tailored and evaluated in the synthesis of variable ranges of design goals. In these particular examples, these ranges are comprised of varying mixtures of material intelligence, constructibility, structural performance, and design authorship. The design goals and basic modelling schema for each project will be outlined individually. This will set the base for a later discussion reflecting on approaches for validation and verification.

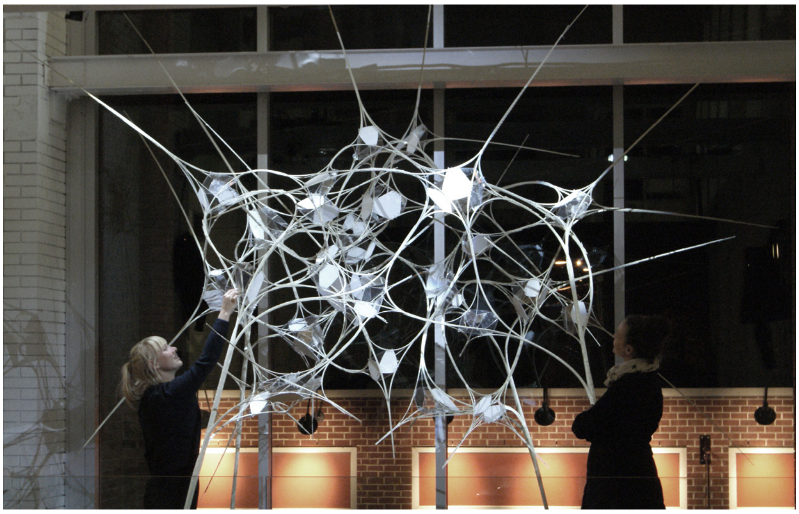


Figure 1: *The ACADIA Rise*

7.3.1 The ACADIA Rise

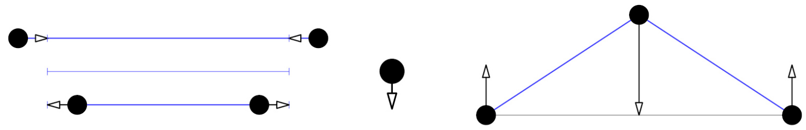
The ACADIA Rise is an architectural installation that extends CITA's research into bending-active structural systems. Here, fibrous and flexible glass-fibre reinforced polyer (GFRP) bundles multiply, bend, branch and recombine at nodes of hard acrylic convex polyhedra that hybridise the assembly into an organically distributed, spaceframe-like spatial structure.

The computational interest for the experiment lies in the production of loosely bio-mimetic, dynamically activated generative models. Their aim is to implement form-finding processes based on recursive algorithms imbued with responsive feedback loops, such that the characteristics of constituent materials are continuously expressed through a simulation of their structural behaviours, occurring as each element is generated during model execution.

The bio-mimetic component of the algorithm is a direct extension of the modelling strategy deployed for CITA's earlier experimental structure The Rise. For both of these projects, "tropisms" that describe the mechanics of

paremeters and executing algorithmic transformations, and also allows for rapid and dynamic extension using text-based user generated scripts.

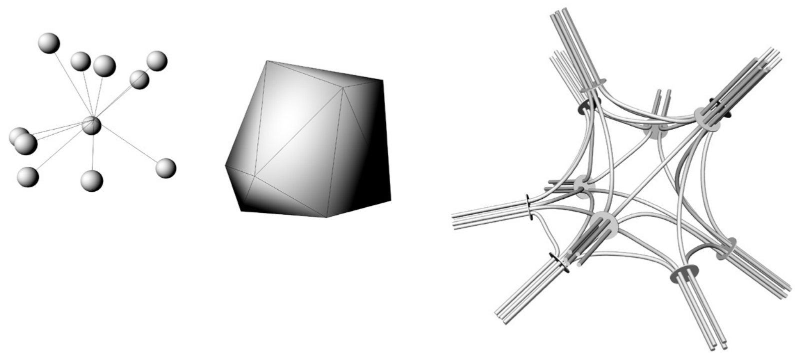
Figure 2: Base forces applied for the particle-spring simulation for The ACADIA Rise. From left to right: 1. Spring, 2. Unary and 3. Bending.



plant growth operate as a type of pseudo-code for the recursive growth process (Tamke, Stasiuk, and Thomsen 2013). In The ACADIA Rise, a set of four initial seed points are located in the target design space. They then sense their environment and extend GFRP shoots toward a virtual light source also located in the design space. As these seeds grow, they also sense proximity to each other. Within a specified tolerance, branches fuse together into triangulated, connective nodes. The formation of each node results in additional outgoing growth shoots, and the total assembly becomes increasingly dense over time. The growth algorithm is dynamically activated through a custom-coded particle-spring simulation system. Through this mechanism, the emerging form is modelled with direct dependence on the material assembly's physical behaviour under self-loading. Critically, the model is also configured to adaptively re-specify the bundle sizes of the GFRP rods and reparameterise the simulation accordingly.

This simulation system relies on a simple continuous Verlet integration of standard "forces" derived from Newtonian physics. It uses three of these common to such models: 1. a spring force that applies Hooke's Law to pairs of particles throughout the simulation, 1. a unary force that acts upon each of the particles to simulate the force of gravity, and 3. a vector-normal bending force that endows sets of three particles with elastic properties, which when laminated consecutively from subdivison points in a spline simulates the behaviours of bending-active members. This last force as implemented here was derived by Barnes, Williams and Adriaenssens (Adriaenssens and Barnes 2001), and later more simply represented by Moritz Fleischmann and Daniel

Figure 3: Digital prototype illustrating use of convex hull topology to develop connectivity and structural organisation of nodes.



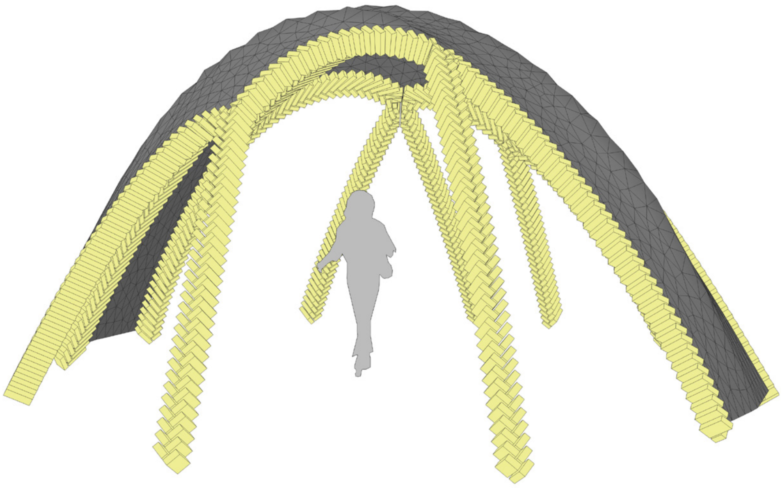


Figure 4: (Opposte) Ribs specified at the resolution of the brick (yellow) and vaults generalised as a coarse mesh (grey).

Piker (who consulted in the coding of the custom simulation library developed here).

The hybrid nature of the structural assembly produces the most significant modelling challenge in the desire for an integrated representation of both the actively-bent elements between and the rigid elements within each node. The digital modelling of the nodes relies on convex hulls created around a spherical intersection with the bending-active splines that meet at a given point. These hulls manage the connectivity between elements in terms of their topological relationship, and simultaneously produce the geometry for triangulated spring forces that stiffen the connection node in the simulation. So the simulation model becomes a hybrid as well: with one set of springs and bending forces describing the struts between nodes, and another set of springs that represent the behaviour of the rigid plates that both define connection topology and stiffen the nodes.

7.3.2 The Utzon(X) Masonry Pavilion

For the Utzon(X) Masonry Pavilion, the ambitions of the design brief are

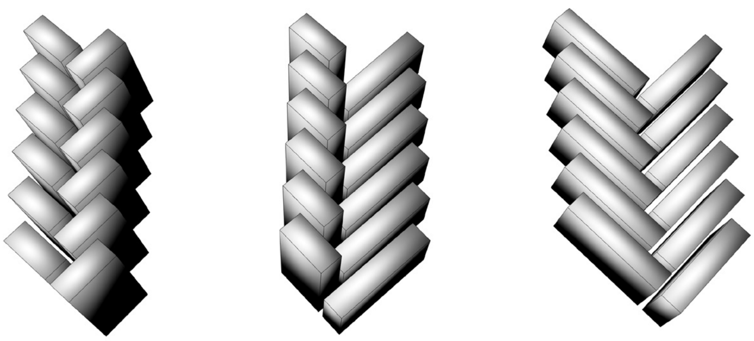


Figure 5: Variable herringbone configurations for precisely specified rib bricks: freestanding column (left) column open on one side and supporting a vault on the other (middle) and supporting vaults on both sides (right).

Figure 6: Rib networks (opposite top) and the scaffolding system for precision location and orientation (opposite bottom).

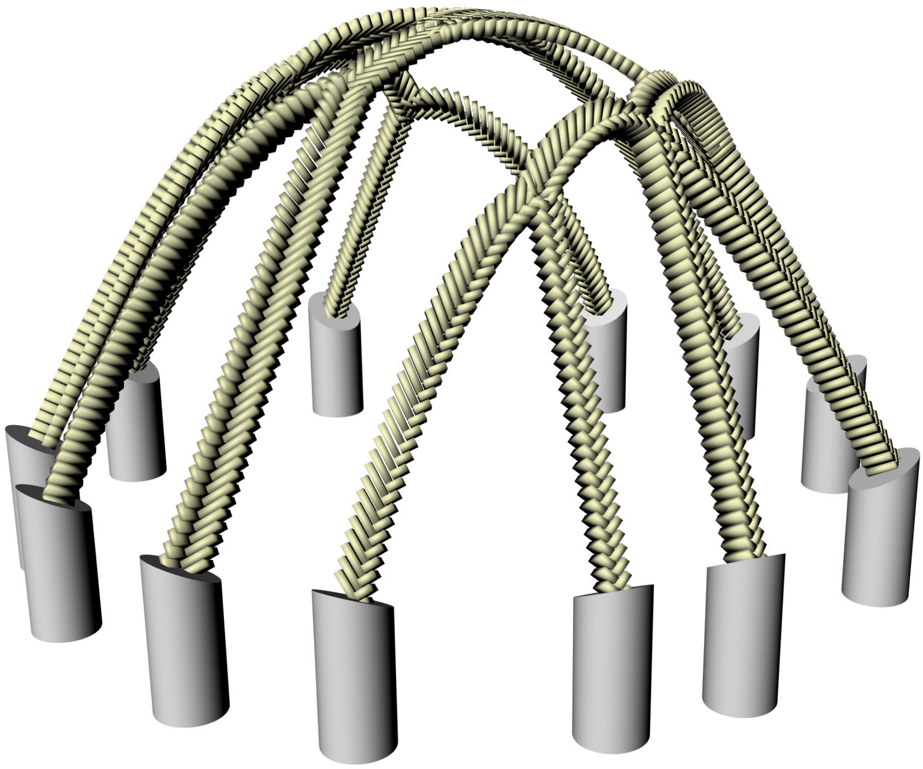
explicit from the outset of the design process. The goal is to produce a funicular vaulted masonry construction within a set building site. This construction must integrate a consideration of its architectural expression with the activation of variable thermal properties from differently coloured bricks. The ambition for the workshop also includes a need to collaborate with advanced masonry students in the development of both prototypes and a final fabrication strategy that is fully considered during the design phase.

In order to make these multiple goals tractable, the modelling process is discretized into multiple stages. The segments discussed here are tied to the model that executes the simulation-based funicular form-finding for the overall configuration of the pavilion and its integration with processes for the digital fabrication of a scaffolding system intended to help direct masonry work in realising the complex generated rib and vault geometries.

The funicular simulation is developed using Kangaroo, a particle-spring physics simulation plug-in for Rhino+GH. The form-finding process relies on a combination of spline-networks for the ribbing, and area-independently loaded triangulated meshes for the vaulting. This allows for the ribs to not simply work as a network of hanging chains assuming individually planar configurations, but also integrates a simulation of the loading that results from the interstitial vaulting, pulling the ribs out of plane as they adapt to manage the self-weight of this more complex configuration.

The construction strategy targeted for deployment in the final assembly is comprised first of precisely located and strategically oriented masonry ribs that carry loads down to multiple discrete concrete foundations, and secondly of the infill vaulting that spans between these ribs. The detailing strategy for the ribs is based on herringbone pattern configurations that are varied according to each rib section's performative role.

The geometry of the vaulting is only loosely specified by the design model and, and is precisely located on-site under the direction of the master mason. As a result of this combination of pre-fabrication precision for the ribs and later in-situ resolution for the vaulting, the model evolves to represent varying degrees of specificity in the design geometry. On the one hand, highly detailed fabrication drivers are produced for the scaffolding used to guide the masons' work along the ribs during construction, which is resolved down to the level of individual bricks. On the other, the vaulting is indicated in the design model as a low resolution series of non-discretised triangulated meshes distributed between the ribs.



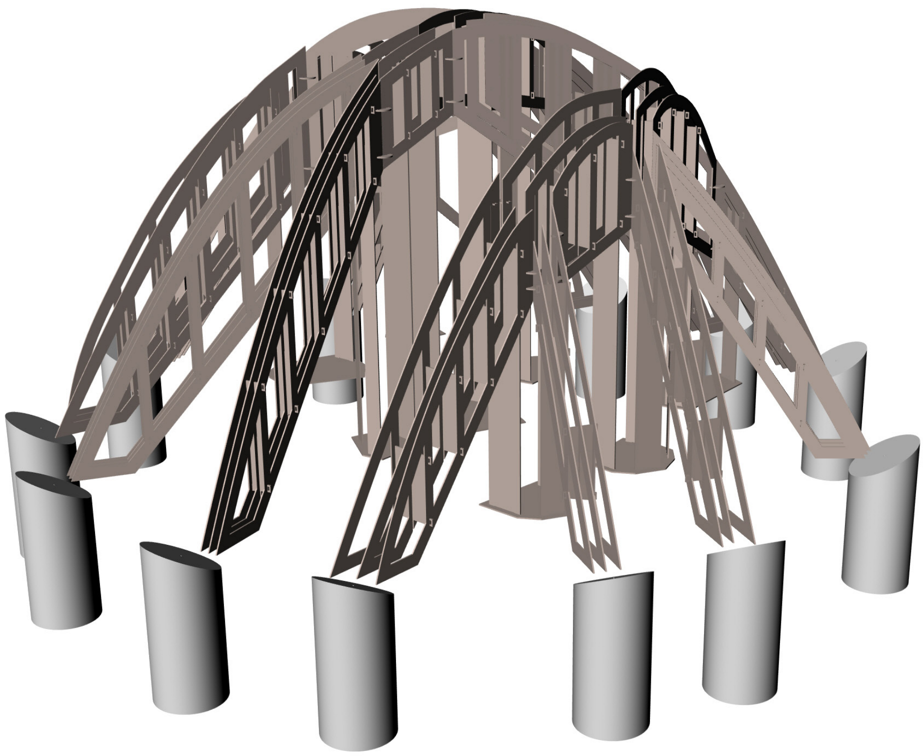


Figure 7: CITA's *Stressed Skins* installation exhibited at the Danish Design Museum in Copenhagen.

Each of these structural elements – the rib and the vault – is treated differently in the simulation, and the inverted weights of each in the catenary simulation are separately controlled by the designer, in order to 1. sculpt the final spatial condition toward the design brief, 2. create a rib geometry for which a scaffold is reasonable to build, and 3. provide the masons with a general vault geometry that is manageable according to the techniques that they employ.

7.3.3 Stressed Skins

The architectural installation Stressed Skins is free-form, frameless stressed-skin structure comprised of two layers of 0.5mm thick steel plates. The connection details between plates on each side provide the structure with depth for managing shear forces within the structure. All of these geometric elements, along with support for connections between plates on the same layer and tectonic patterning are robotically asserted through a process called single point incremental forming (SPIF).

The computational interest for the experiment lies in the dynamic activation of a multi-resolution unstructured mesh that adapts across multiple scales of design inquiry. It works as the underlying data structure for a variety of interdependent form-finding operations, structurally and materially-driven simulations, and direct fabrication drivers for CNC operation.

Form Finding

The initial form-finding process relies on a generative growth algorithm that distributes two regular pentagonal tiling tessellations onto two free-form doubly-curved target design surfaces. The tiles themselves are instantiated using two .NET libraries that are directly integrated with the Rhino+GH modelling environment. The geometric and topological basis for the model is managed using the first of these, a half-edge mesh data structure called Plankton. The form-finding simulation is then executed through a beta-version of the constraint (or "goal-oriented") physics-based Kangaroo2 library (Piker 2015). Through a direct scripting interface, Kangaroo2 enables the writing of custom goals over dynamic and transforming topologies. Because the tiling scheme used is developed for a planar condition, here individual tiles must be distorted in order to follow the geometry of the target surfaces. In the form-finding simulation, a collection of goals is used to resolve competing geometric assertions.

The base goals are related to edge-length maintenance and internal bending angle for each pentagon. Next, goals that draw each vertex to the appropriate target surface and repel it from the opposite (either for the upper or lower skin) are established, as well as a goal for polygonal vertices on opposite skins to repel each other, aiming to increase heterogeneity in panel connections between the two skins and minimise potential "hinging" instances. Finally, the introduction of a planarising goal is necessary to ensure each panel is suitable for fabrication.

Figure 8: (Opposite) Interior view between upper and lower skins showing formed connections and patterning.

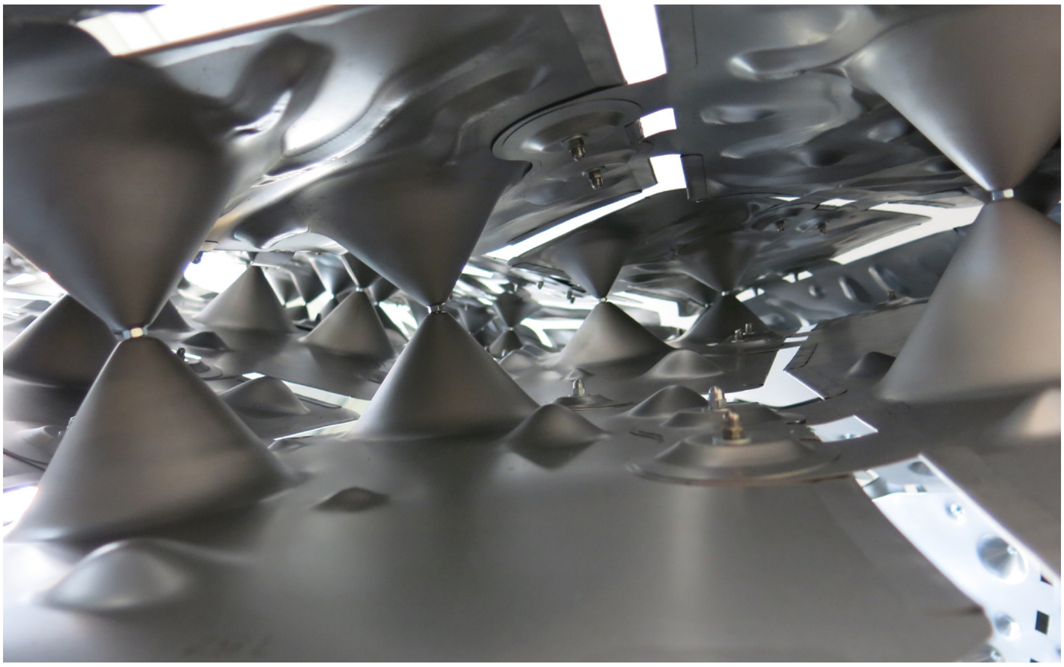
Tectonics

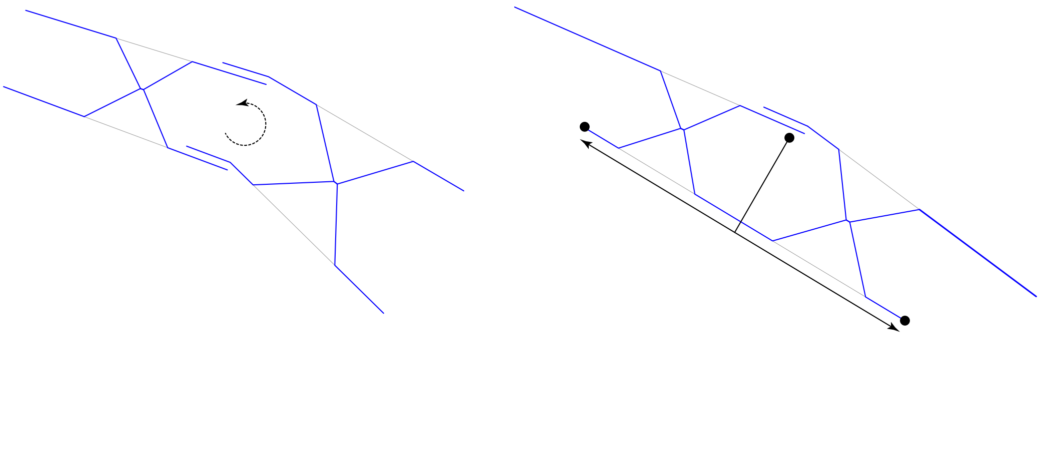
Following the initial form-finding operations, a series of structural finite element simulations are executed, using the Karamba component group for Rhino+GH[5]. First, shared territories where formable areas able to accommodate connections on both skins are identified, and "probe" connections are located within each of these territories. Then these probe connections are used to execute a finite element analysis, the results of which drive a further transformation, where connections multiply and reorient themselves in response to shear forces read. A second finite element analysis is then performed on this organisation, the results of which drive are used to create the two distinct tectonic patterning systems, one for the lower skin and one for the upper skin. The lower skin pattern is simpler, and comprised of a series of dimples located in response to high utilisations within each panel, and then secondarily oriented according to shear forces read from adjacent inter-skin connections. The upper skin pattern is more complex. First, its base form is globally derived through a Gray-Scott reaction diffusion simulation (McGough and Riley 2004).

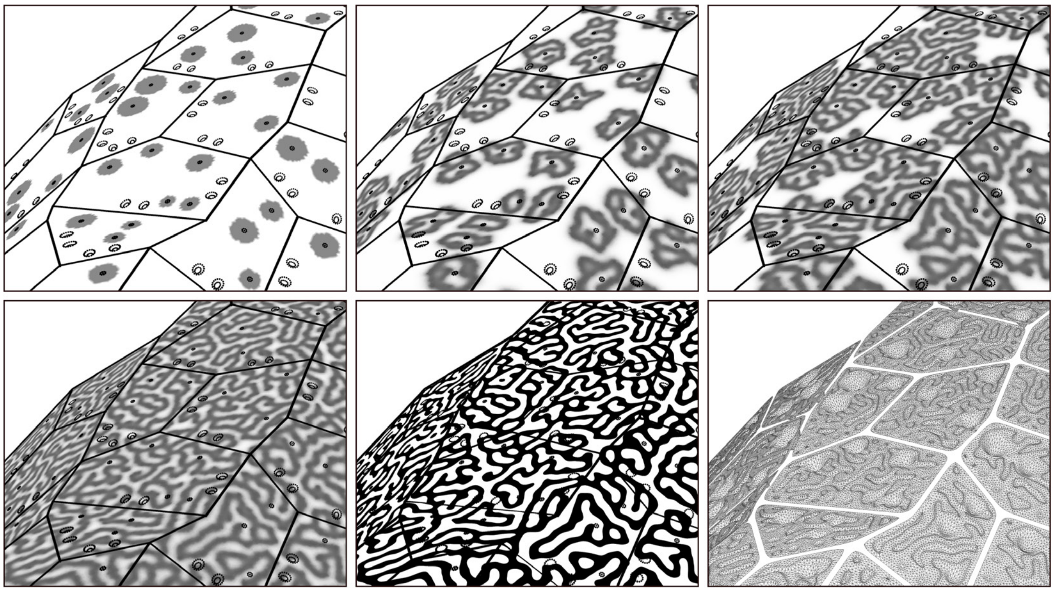
Figure 9: (Opposte) Undesirable hinging condition (left) where seams align along both skins, andvertex repelling goal to minimise these instances (right).

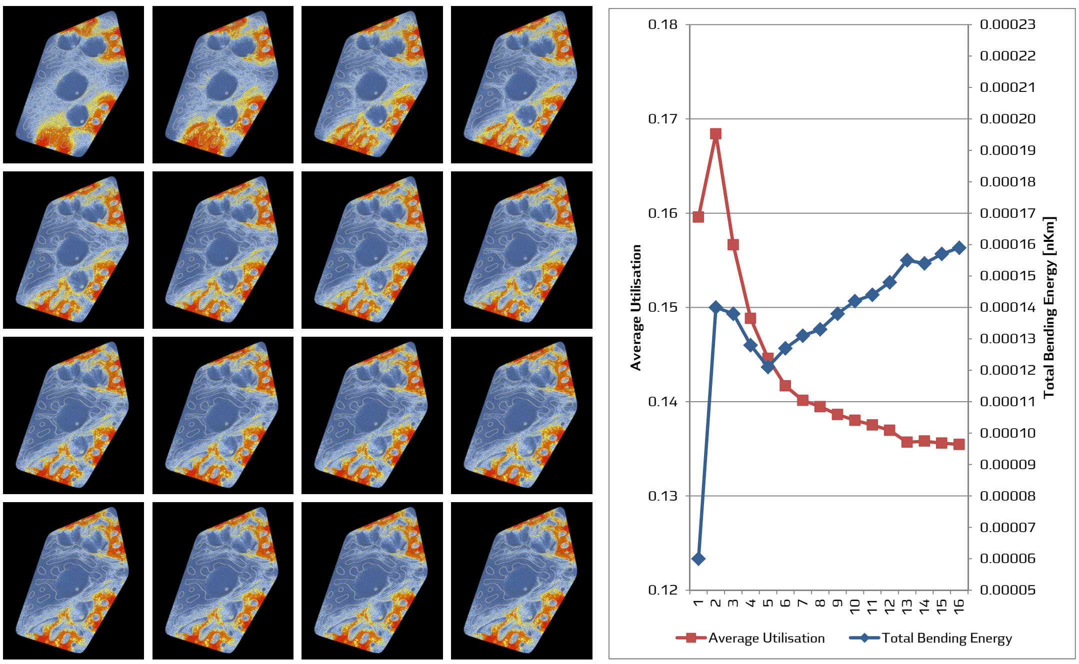
Each panel is then discretised, and in a third series of finite element analyses subjected to translational and rotational forces derived from the second finite element analysis described above. Here, high levels of utilisation are identified, and used to locally activate an incremental introduction of depth to the reaction diffusion pattern. This in turn is used to recalibrate the local material properties within each panel, such that increases in stiffness related to increased geometric depth and hardness related to plastic deformation resulting from the forming process can be registered. Then these data are used to update the model, which is re-iterated through the same force application and responsive introduction of depth. This loop is run up to 15 times for each panel, locally introducing material transformations in response to the simulation of their local structural responsibility within the global assembly. The result is both

5 The initial model setup was created with direct consultation from Clemens Preisinger and Robert Vierlinger of Bollinger + Grohmann








Average Utilisation
Total Bending Energy [nKm]
0.18
0.17
0.16
0.15
0.14
0.13
0.12
0.00023
0.00022
0.00021
0.00020
0.00019
0.00018
0.00017
0.00016
0.00015
0.00014
0.00013
0.00012
0.00011
0.00010
0.00009
0.00008
0.00007
0.00006
0.00005
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
Average Utilisation
Total Bending Energy

an overall reduction in utilisation due to strain hardening combined with an increase in the total bending energy potential for each panel.

7.4 Results and Discussion

Figure 10: (Opposite) Reaction diffusion simulation run on global mesh to array upper skin patterning, then integrated with inter-skin connections and discretised for each unique panel.

Each of the experimental models described above relies on simulation as a key form-finding instrument, through which it represents dynamic material behaviour in its generative algorithm. Although all of them use variations of a particle-spring system for the primary form-finding operations, each has its own particular setup, and crucially is developed with different design ambitions for output. The ACADIA Rise is focused almost exclusively on the dynamic representation of a bending-active hybrid material assembly. The Utzon(X) Masonry Pavilion seeks to work with the well-understood potentials and behaviours of catenary vaults, but in a way that allows for the designer to trade an ideal structural capacity for a more nuanced management of spatial intent and fabrication potentials. Stressed Skins iterates through multiple stages and types of simulation. First, it deploys its goal-oriented particle-based simulation model almost exclusively through artificial forces that execute the generative form-finding algorithm and refine geometry for the purposes of fabrication. Then it uses finite element approaches to analyse structural behaviours and materials properties in its location and specification of connection details and in its tectonic expression.

Figure 11: (Opposte) Finite element transformations over 15 iterations of locally introducing depth and updating material properties for each panel (left) with related decreases in total utilisation due to strain hardening and increases in bending energy due to added geometric depth (right).

7.4.1 Verification for design simulation

A strong theoretical basis for the calculative techniques used is critical for sanctioning simulation models in the natural sciences. Their purposes include testing or extending these existing theories, building deeper knowledge about complex phenomena around the systems they describe, and predicting specific outcomes for a set of conditions in their domain of interest. As a result, they must be verified – or here "calibrated" – through a few clear methods: either through experiments, analysis, or other previously validated simulation techniques (Winsberg 1999). In each instance, the purpose for such models is to either achieve a maximum fidelity in their representations. Simulation for form finding in architectural design may be judged on somewhat different criteria.

Prototypes

Physical prototypes have long played key role in the development of architectural design systems, and indeed have become even more essential as digital computation techniques enable a greater range of modelling flexibility:

> *The relation between model of design and prototype gains importance as our understanding and relating of material systems to their simulated abstract models improves and computation increasingly becomes embodied in physical constructs replacing complex mechanical assemblies with computational feedback and control (Gengnagel et al. 2013).*

This ties directly into the role they play in the calibration of design simulation models, and is particularly applicable for those that are exploring new territories, techniques, material performances, or structural assemblies. For such systems where a theoretical foundation or precedent simulation schema may only partly validate model setup, engaging in parallel prototyping practices to evaluate the simulation system as it is being developed becomes necessary. Here, vital information for feeding back into the digital model is collected regarding material transformation, assembly performance, fabrication applicability, and global structural behaviours.

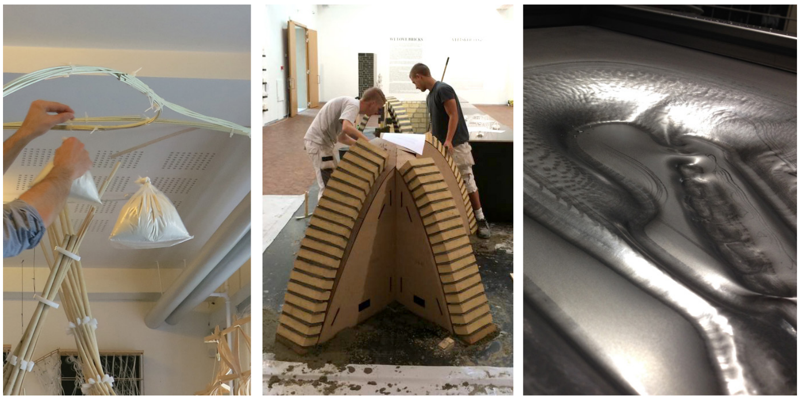


Figure 12: Prototyping for global structural behaviours in The ACADIA Rise (left), for the development of fabrication techniques in the Utzon(X) Masonry Pavilion (center), and for understanding material transformation for StressedSkins (right).

Authorship

In the case studies discussed, the variation in technique and simulation model formulation are driven by more than a theoretical understanding of the systems they endeavour to represent. As mentioned above, each is driven by its own set of design ambitions. It is these ambitions that drive the adaptation of what particular simulations need to – or even should – represent. This is a direct result of the projective nature of design, and what separates the artificial sciences from the natural sciences. Sanctioning a simulation model for architectural design relies on its capacity to correctly describe a material or assembly system insofar as the author prioritises this in the context of other design ambitions that may lie outside of the simulation's purview. So this fidelity works as one weight in a balance of complex intentionalities – such as those appropriate for addressing the wicked problems that designers face – and has its own range of acceptable tolerances. As design simulationists pursue the ongoing development of better techniques for embedding material intelligence and complex assembly logics into digital simulations, they will continue to collapse these tolerances, and more clearly assert their authorship even as they take advantage of open-ended explorations in form-finding.

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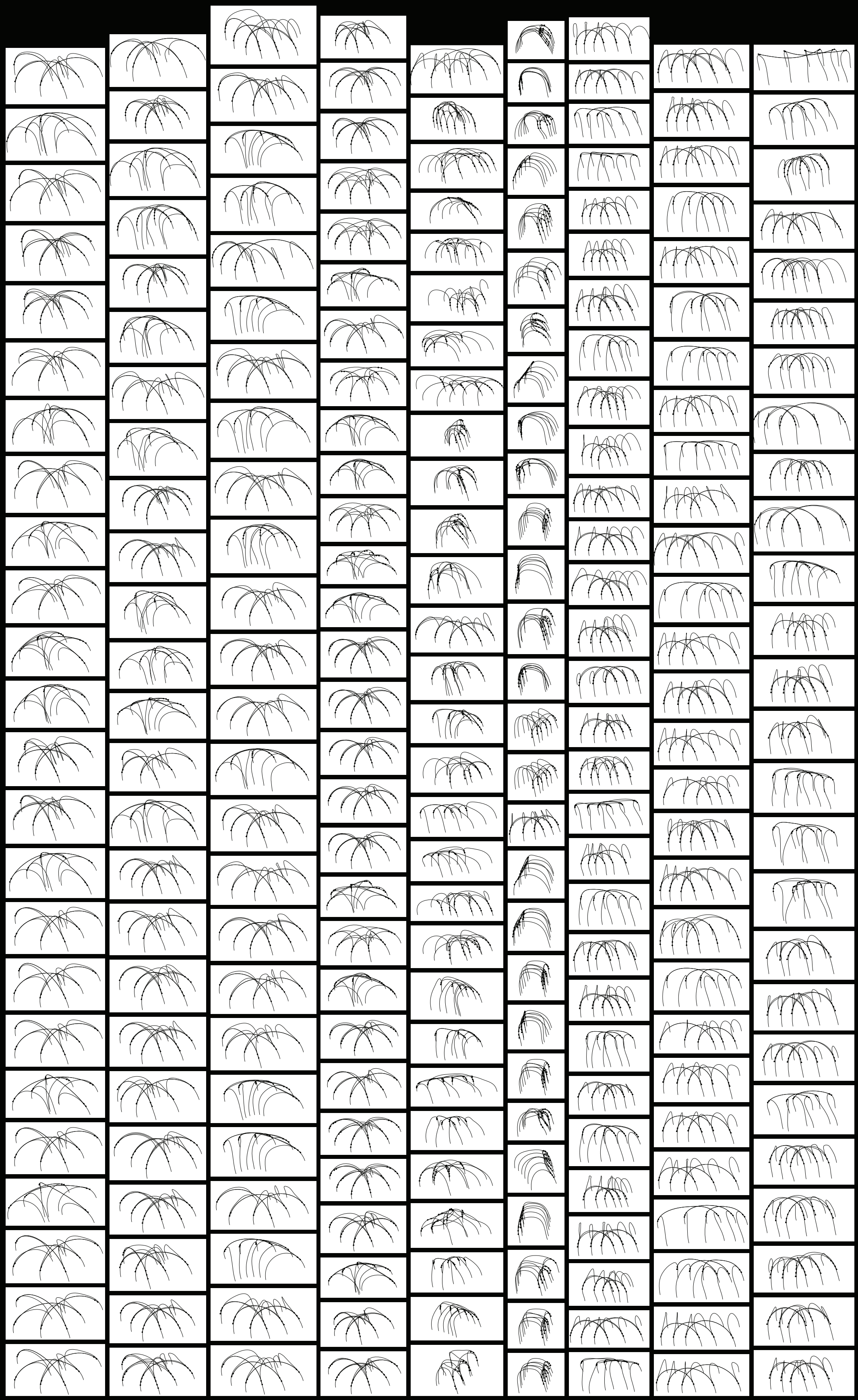
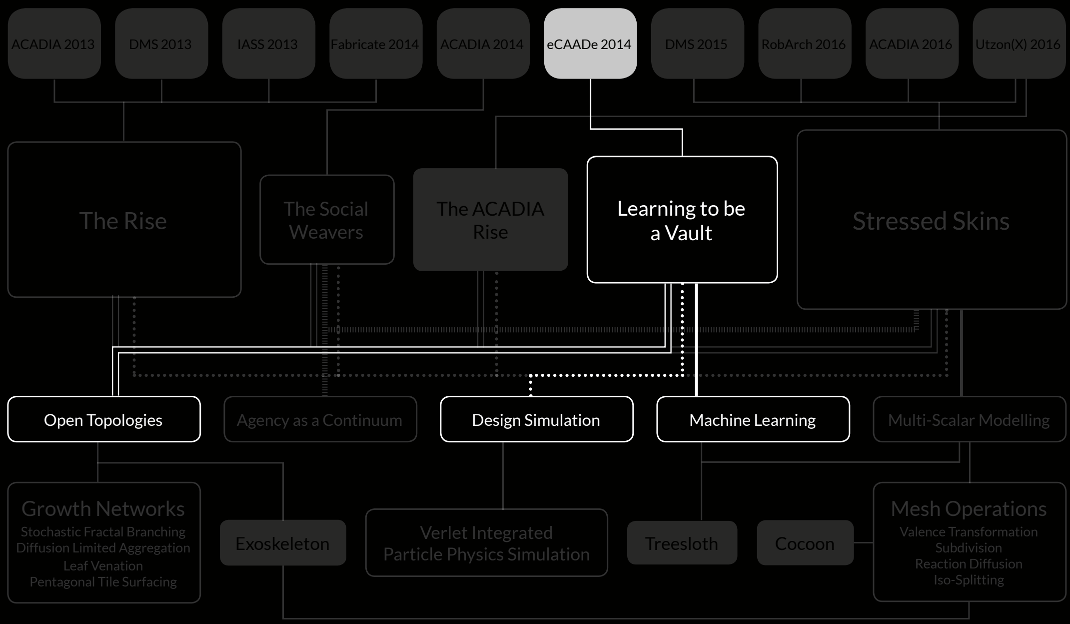




Publications IV: Learning to be a Vault

The publication presented here is related to my role in the development of the experimental project *Learning to be a Vault*.

> Stasiuk, D., Thomsen, M. R., & Thompson, E. M. (2014). *Learning to be a vault—implementing learning strategies for design exploration in inter-scalar systems*. Newcastle upon Tyne, England, 381-390.

Engaging in Machine Learning

Although *Learning to be a Vault* continues an interest in both open topologies and design simulation, it marks a significant break from prior projects – *The Rise*, *The Social Weavers*, and *The ACADIA Rise* – in that while it continues to use the simulation of material properties to activate adaptive data substrates for information capture during morphogenesis, it extends this framework toward the use of machine learning techniques for the pursuit of increasingly adaptive parameter spaces. The aim was to produce an algorithmic modelling system that exhibited a form of emergent parameterisation, whereby simple geometric analyses of model forms produced through an open-ended design system may create new classification criteria – parametric descriptions of model morphology – for novel and efficient means of searching the design space.

The paper outlines how k-means clustering is applied to large collections of "optimised" model phenotypes to rapidly categorise or classify model instances according to properties that could not easily be described, but which would be readily apparent in observation.

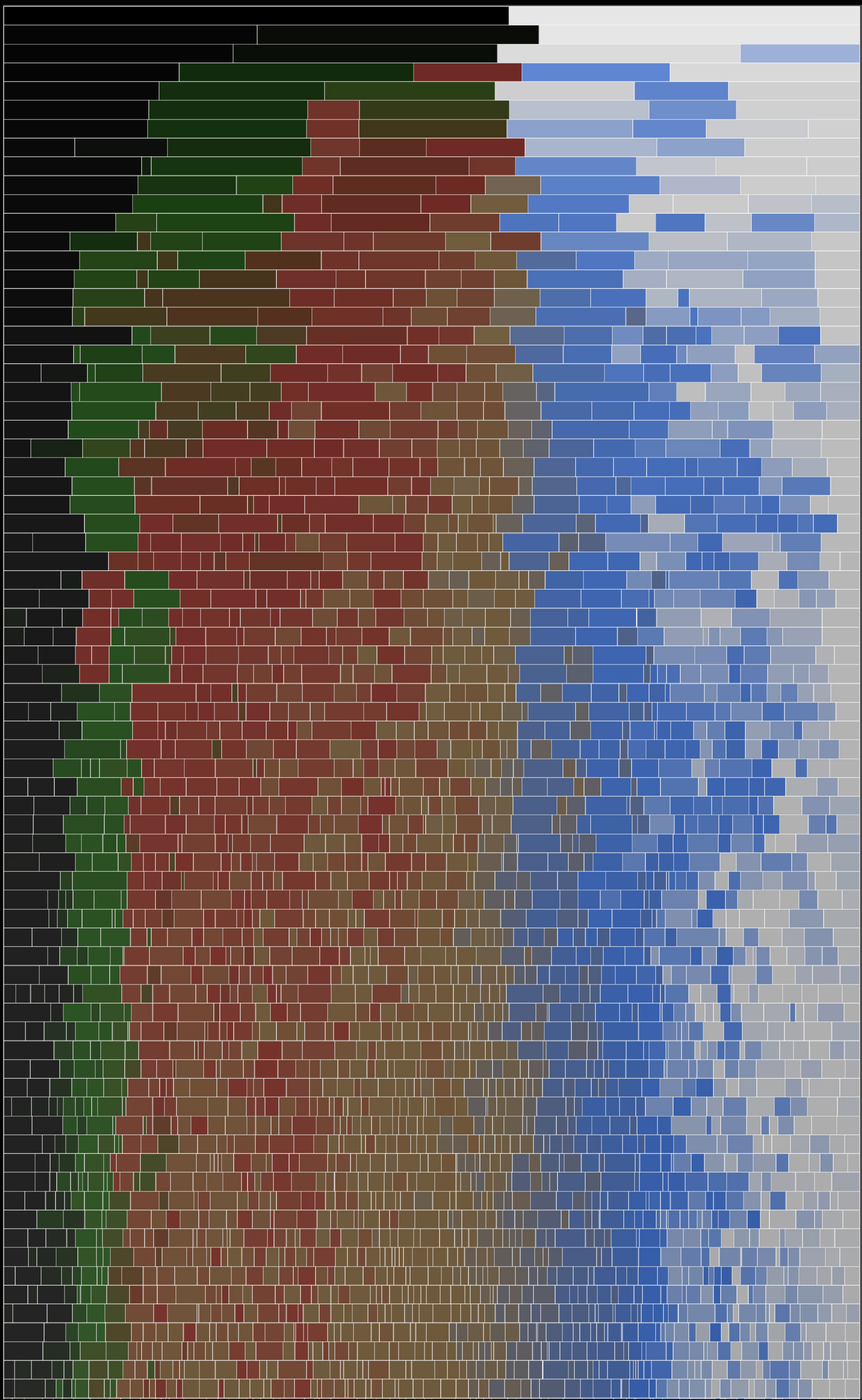
Project Role

As lead researcher for this project, I developed the modelling systems used throughout the project, including: the design probes, simulation systems, generative logics, analytical systems, representational engines, and fabrication drivers. I closely collaborated with my advisor and co-author, Mette Ramsgaard Thomsen in the project's conceptual formulation, hypotheses, and research aims, and I led its design and development.

Author role

As the primary author for this publication, I contributed all of the text, responding to feedback provided by my thesis advisor and co-author, Mette Ramsgaard Thomsen.

Figure: (Opposite) A visualisation of continuity between incremental numbers of clusters produced through the k-means clustering algorithm. As additional clusters are introduced, the colors register similarities between the contents of each cluster.



8. Learning to be a Vault: Implementing learning strategies for design exploration in inter-scalar systems

Reformatted from: Stasiuk, D., Thomsen, M. R., & Thompson, E. M. (2014). *Learning to be a vault—implementing learning strategies for design exploration in inter-scalar systems*. Newcastle upon Tyne, England, 381-390.

Abstract

Parametric design models enable the production of dynamic form, responsive material assemblies, and numerically and geometrically analytical feedback. The value potential for design produced through the procedural transformation of input parameters (or features) through algorithmic models has been repeatedly demonstrated and epistemically refined. However, despite their capacity to improve productivity and iteration, parametric models are nonetheless prone to inflexibility and reduction, both of which obscure processes of invention and discovery that are central to an effective design practice. This paper presents an experimental approach for the application of multiple, parallel computational design modelling strategies which are tested in the production of an inter-scalar model array that synthesises design intent, the simulation of material behaviours, performance-driven adaptation, and open-ended processes of discovery and categorical description. It is particularly focused on the computational potentials embedded in interdependent applications

of simulation and machine learning algorithms as generative and descriptive drivers of form, performance, and architectural quality. It ultimately speculates towards an architectural design modelling method that privileges open model topologies and emergent feature production as critical operators in the generation of flexible and adaptive design solutions.

8.1 Introduction

Although parametric modelling allows designers to dynamically produce variable geometries and execute sophisticated analyses of performance attributes, certain problems of both rigidity and reduction endemic to such design systems are well documented. Parametric models are limited because they necessitate a predetermination of both model topology and the feature domains that constitute the model's parameter space. As such, the designer either must explicitly define all parameters and relationships between model elements at the start of the design project or risk breaking the model during any ensuing reconfiguration (Davis 2013). This rapid calcification of the design space is antithetic to the experience of design as a process of invention and discovery. A second problem is associated with risks in the oversimplification of descriptive parameters such that the defining design criteria ignore or suppress potentially useful information embedded in the model output. While this implicit reduction preserves design control and makes the creation of the model tractable (Davis 2013), the resulting limitations act as an impediment to a more exploratory design practice. These problems are only compounded by an increasing sophistication in design models' ability to represent in both the production and analysis of a number of useful characteristics, such as material assembly behaviours, occupation patterns, or energy-related performances. An increased facility in designing for and with these considerations is central to continued innovation in design modelling (Tamke et al. 2011). However, this increased capacity also offers the opportunity to explicitly describe the complexity of the design problem at hand, and in response develop open-ended design systems that have the capacity to address them (Cariani 2008). For this reason, there remains a significant need for the ongoing development of tools through which we can flexibly capture and understand complex interstitial dependencies across model elements for directed performances and as a means to enhance the pursuit of invention and discovery in the development of design models.

This paper traces the exploration of new methodologies in this pursuit, specifically addressing the related desires to maintain open feature domains for both design and evaluation, in order to alleviate requirements for the pre-configuration of both value and element connectivity. It also describes the related pursuit of simultaneously embedding material behaviours in morphogenesis and producing multiple targets for performance optimisation. The aim for the project is to establish methods for designing with open topologies in which the dependencies between parameters are both emergent and changeable during the design process. To this end, an experimental approach is implemented for multiple computational strategies, applied in parallel and sequential operation in the digital environment.

8.1.1 Background

This project takes its point of departure from an intensive workshop with the Digital Matter Master's studio, led by Areti Markopoulou at the Institute for Advanced Architecture Catalonia (IAAC) in early 2014. This workshop introduced multi-objective evolutionary solvers operating in a simulated material context. Through a series of physical models using simple rattan splines and connector ties, seven teams focused on the development of generative design algorithms that synthesise material behaviours, the topological transformation of connectivity between constituent elements, and quantitative, multiobjective optimisation design goals. Through the exploration of these networks as morphogenetic ruledriven systems for incremental formation, a series of variables available for deployment in a multiobjective evolutionary model were then developed. The set of simple goals that emerged from this process of rapid physical prototyping were related to material usage, the generation of space and structural performance and capacities. Measures related to connectivity and material deflection define those goals related to structural performance, and the coupling of the conflicting goals of minimizing material use while maximizing envelope size provided simple spatial performance goals. What emerged through these iterations was a series of rigorous pseudocode algorithms for both generation and evaluation. The distinct approaches of each team established a framework for developing a more general design system capable of generating multiple, highly varied configurations, that nonetheless retain formal and organisational legibility.

8.1.2 Learning to be a Vault

"Learning to be a Vault" is an experiment consisting of a significant digital exploration and consequent representation of the design space, along with the production of 25 1:25 models and a 1:1 demonstrator approximately 5 x 5 x 2.5 m. It has been installed as part of the "What does it mean to make an Experiment" exhibition at the Royal Academy of Fine Arts School of Architecture during the Spring of 2014. The IAAC workshop operates as a baseline for the formulation of this experiment, which focuses on the synthesis of multiple computational strategies implemented in an inter-scalar modelling environment. Of particular interest is the deployment of machine learning algorithms. One possible strategy for advancing the flexibility of parametric models as performative instruments is tied to rethinking how parameters (or features) are treated in the modelling space. Typically, feature domains are established as inputs for the geometrical outputs of an architectural design model (Davis 2013). However, there are opportunities to recast certain features in a parametric model as either dynamic or descriptive entities, enabling the designer to engage in alternative means to search the design space. For this experiment, the focus is tied to using machine learning algorithms to classify large collections of model outputs generated through a multi-objective evolutionary optimisation solver into legible groups – or species – of response.

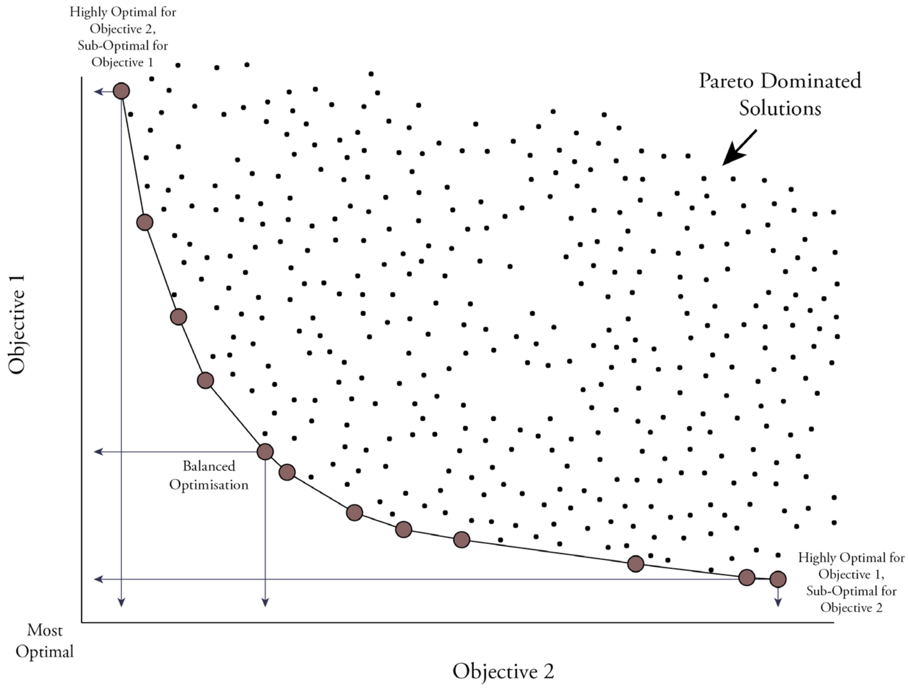
In "Learning to be a Vault", there is a tight integration of three distinct modelling systems. The first is a generative model, constructed with the considerations developed through the workshop described above. It recursively builds up networks of activelybent splines that have the capacity to achieve great variety in form. Intrinsic to this model development is not only the topological connectivity established through the generative algorithm, but also a springbased form-finding simulation of the design material, which is rattan, a soft but highly flexible wood-like plant. The second model is a multi-objective evolutionary optimisation solver, which leverages the generative model input parameters as its genotypes and its outputs as its phenotypes. These phenotypes are subsequently analysed for five distinct performance measures. Finally, the outputs from this model are analysed using k-means clustering, an unsupervised learning algorithm that identifies intrinsic relationships between the data elements of its input data points. This analysis takes on the form of classification, which allows for an intuitive understanding of many outputs as belonging to legible and distinct groups. The following section will briefly discuss machine learning in general, and in the context of computational design models, will then offer focus more on the relevant machine learning strategies used in this particular experiment.

8.2 Machine learning in computational design models

Machine learning is a field of research and practice related to developing computer programs that are configured to improve their performance at a given task through experience (the acquisition and processing of incremental data) (Mitchell 1997). It is focused on three primary categories of interest: task-oriented studies, cognitive simulation, and theoretical analysis (Carbonell, Michalski & Mitchell, 1983). For task-oriented studies, machine learning is largely interchangeable with the field of statistics, as many predictive algorithms (such as linear or logistic regressions) are used extensively in both. Task-oriented machine learning is primarily concerned with the classification of data points as function values within some descriptive domain. These domains are most often discrete (e.g. Boolean, integer, or categorical values) but can also be continuous (e.g. real numbers). Learning models are divided into two main types: supervised and unsupervised.

Supervised learning models rely on training data where the predicted outcomes are known, so that the model develop input (or feature) transformations and weights that will allow it in the future to more effectively predict the outcomes for unknown data. As each new evaluated data point used (or instance) for training has its actual outcome determined, the learning model gains new intelligence about its performance and recalibrates itself according to its driver algorithm. Unsupervised models operate differently. They allow for the features of data sets to self-organize. These are primarily used for the discretisation of data into descriptive or functional categories, without the need for training data. In effect, when the outcomes are unknown, unsupervised learning algorithms are designed to allow for the internal relationships within the features of a data set to create emergent descriptions of each instance.

Both supervised and unsupervised learning models are often used discretely to resolve subcomponents of larger problem spaces. In effect, the outcome of any learning model is simply a new feature for application in a new decision space. Both supervised and unsupervised learning approaches have precedent in architectural design modelling. Their applications have been theorized for nearly as long as CAD systems have been in use, but in the last twenty years – and increasing in step with advances to the processing power of personal computers – their implementation has become tractable and in many cases standardised. The most commonly used learning algorithms in design modelling are genetic or evolutionary solvers, whose epistemological and functional maturity in the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Pareto Dominated Solutions
Objective 1
Balanced Optimisation
Highly Optimal for Objective 1, Sub-Optimal for Objective 2
Most Optimal
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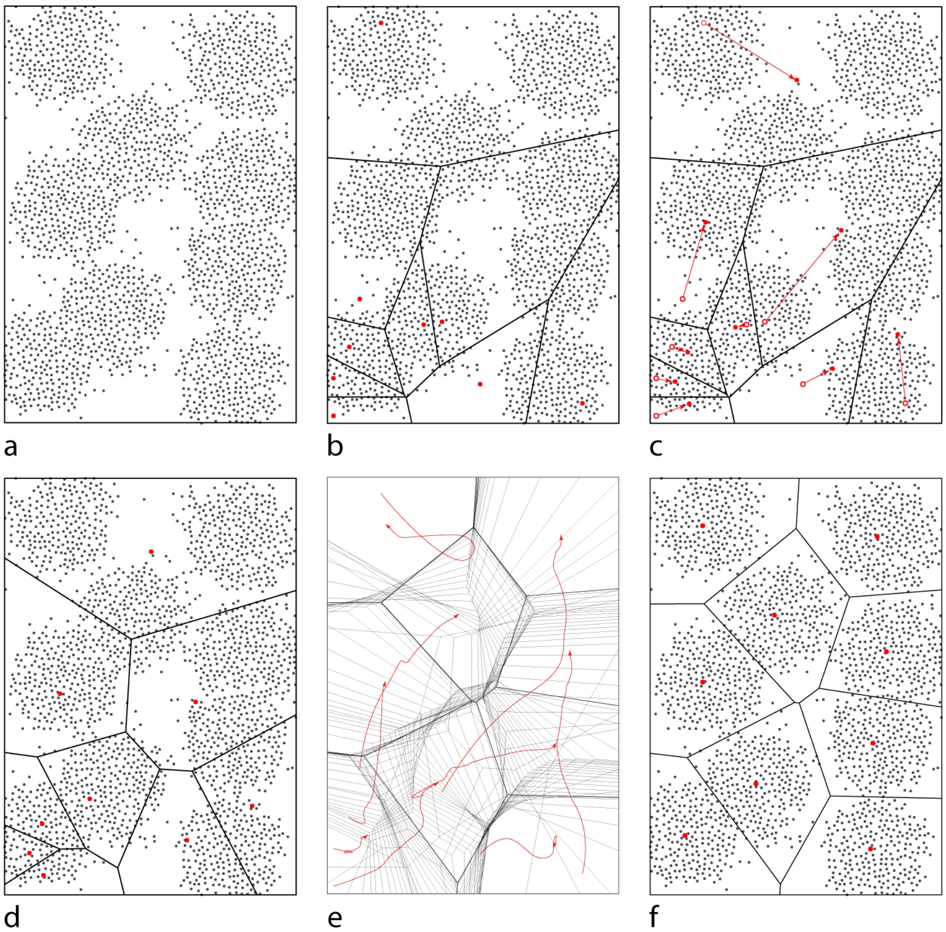
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design sciences far outreaches that of other modes. However, several of those other, lesser-used approaches – which include neural networks of multiple types and k-means clustering algorithms – have nonetheless been successfully implemented in the past and present excellent opportunities for the future extension of learning algorithms in design modelling. For the purposes of this experiment, we will focus on two of these: multi-objective evolutionary solvers and the k-means clustering algorithm for classification. Additionally, spring-based particle simulation systems will be examined according to the criteria used for establishing that an algorithm constitutes a learning system.

Figure 1: (Opposite) Example of a Pareto front for a two-dimensional objective optimisation

8.2.1 Multi-objective optimisation

Evolutionary algorithms have been applied in the field of architecture for over twenty years, most popularly with the pioneering work of John and Julia Frazer in Department 11 at the Architectural Association, starting in the late 1980's (Frazer 1995). In a rough summary of their operation, they rely on a generative system for the parsing of inputs (genotypes) into outputs (phenotypes), which are then subjected to a performance analysis – most often numerically represented. They begin with a pool of randomly assigned genotypes, test the performance of resulting phenotypes, and then "breed" the most successful offspring through the crossover (and potential) mutation of genotypes. Over time, this process allows for successful genotypes to thrive and pass on their parameters to their children, and is repeated through a number of generations until satisfactory objective values have been achieved by the resulting phenotypes. Because evolutionary solvers rely on setting explicit targets for performance measurement, they can be understood as supervised learning models, with the optimisation objectives used for training.

Figure 2: (Opposite) K-means algorithm on a twodimensional data set with k=9: a) data array, b) boundaries for k random sample points, c) test for inclusion and move centroids, d) redefine boundaires, e)repeat c & d until stability, f) stable solution

In an architectural design context, there are key considerations for making this approach tractable. There must be a balance struck between the model's ability to produce an artefact that is recognisable as a built object, but also a capacity for the model not overly limit the range of possible outcomes (Janssen et al. 2000). This can be understood as a simultaneous desire for legibility and variety in the outputs of such models.

As the computational tools available for executing evolutionary algorithms have become more accessible, so has the capacity to introduce many parallel objectives into a single model. The concept of n-dimensional objectives in such design models is keyed around the Pareto front, which operates as a means to understand the outcomes of the design space (Figure 1). The Pareto front is defined by a boundary of phenotypes whose optimisation values define a convex hypervolume in the n th dimension, with n being the total number of optimisation objectives. For example, single-objective search will result in a point, with a single, optimum phenotype. A two-objective search will result in a convex polyline, and a three-objective search will result in a convex triangulated hull. Each phenotype that constitutes the Pareto front can then be said to be "optimised" in some capacity. The front communicates the tradeoffs that exist between phenotypes: as a phenotype demonstrates better optimisation for one objective, it loses value for another. The Pareto front is convenient to visualise these performance trade-offs in up to three dimensions (Caldas 2003), but becomes significantly more difficult to understand once it defines a hypervolume in four or more dimensions. Compounding this difficulty in navigating performance objectives is the fact that as the front's dimensionality increases, it is comprised of a great many more constituent phenotypes, potentially resulting in thousands of Pareto-optimised candidates (Winslow, et al. 2010).

It is, however, this volume of phenotypic output that must be addressed if the continued advances in analytical computational methods are to be synthesised in multi-objective architectural design models. This experiment then deliberately identifies an objective space that produces such a volume of output, and engages in the use of a second learning algorithm to allow for the designer to engage in a form of search that encourages a process of discovery.

8.2.2 K-means clustering

K-means clustering – also known as Lloyd's algorithm – is a distance-based, unsupervised learning algorithm that uses intrinsic relationships between data points in large sets to discretise them into clusters containing the most similar instances. K-means clustering achieves this by using the Euclidean distance between data points in n-dimensional space (where n is the number of features used to drive the clustering algorithm) to find solutions for similarity for a user specified k number of clusters. It does so through an iterative process of computing the "nearest-distance centroid rule", which can be visualised as a voronoi diagram. The algorithm begins by assigning k-number of random points in the data as centroids for the diagram. It then evaluates all of the other points in the set, and assigns them to a "cluster" based on the voronoi boundary containment. Then, the average value of all contained data points is used to recalculate the centroid of the voronoi diagram. This process is repeated until the cells achieve a stable state such that data points no longer move between clusters, and thus centroids no longer require recalculation.

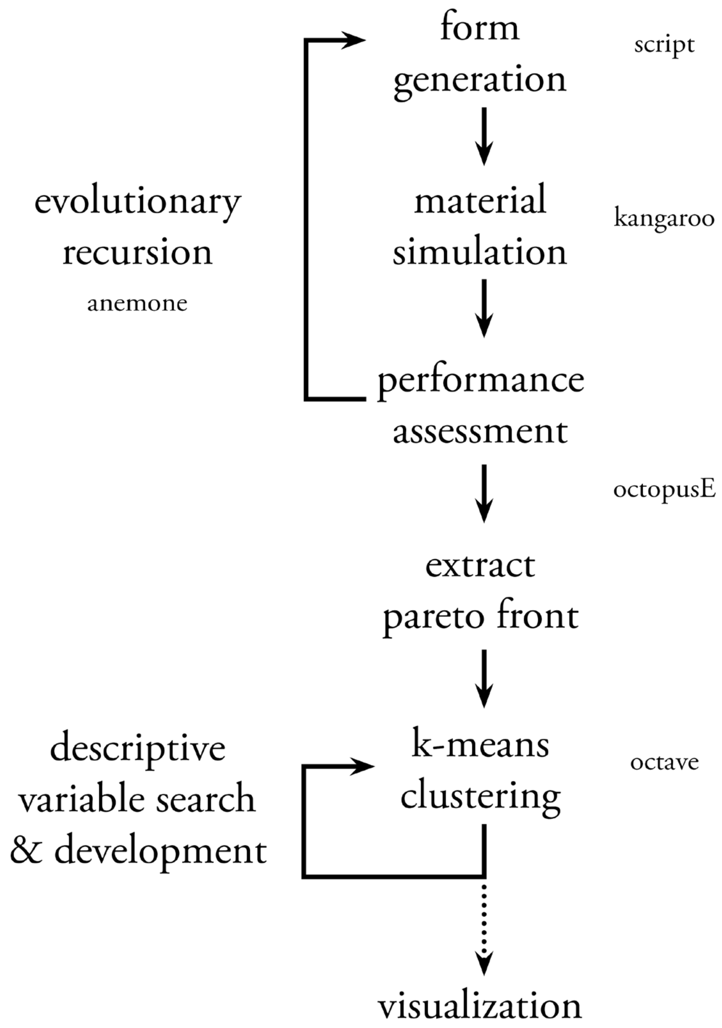
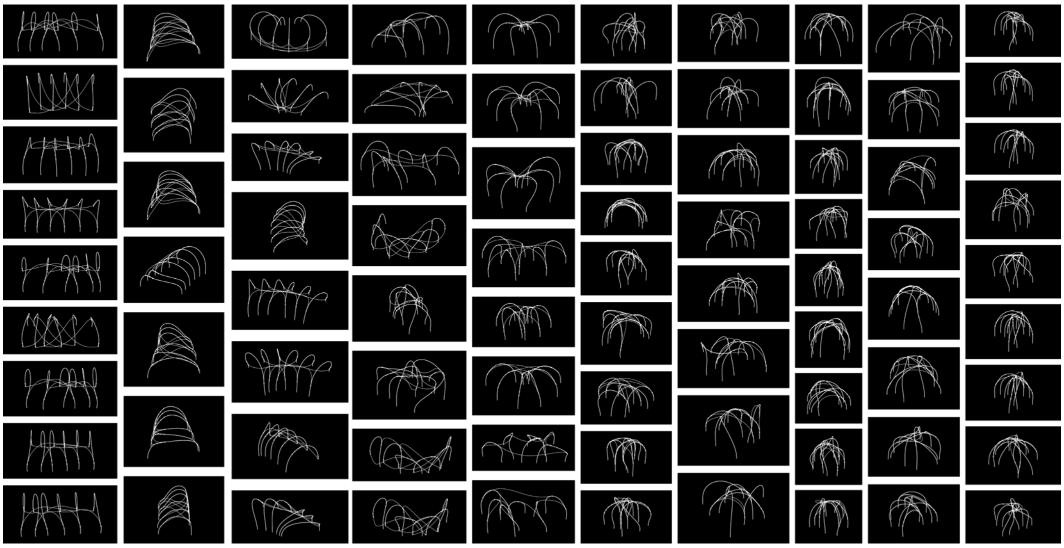
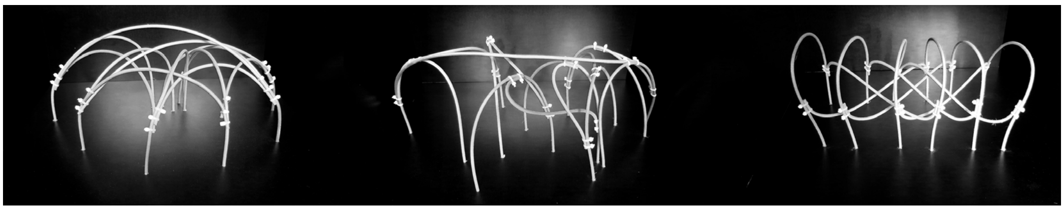


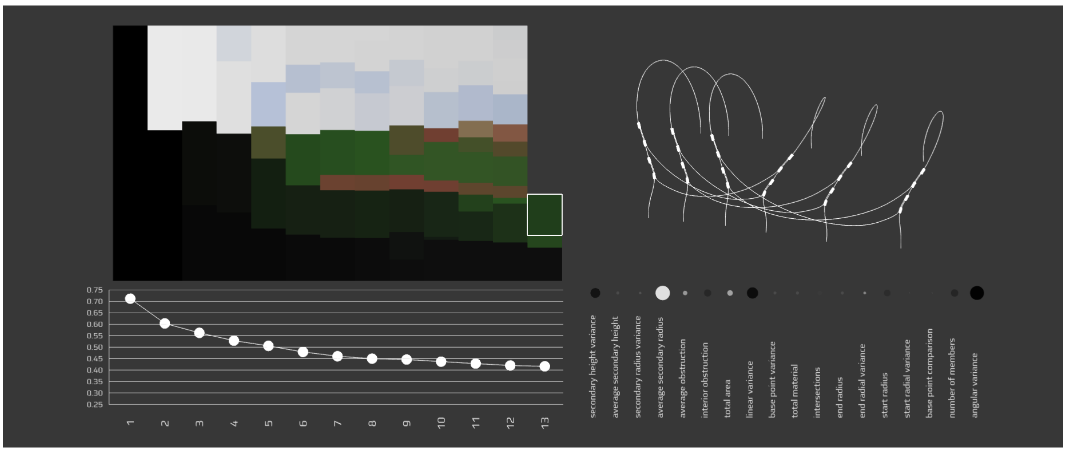
Figure 3: Process diagram for "Learning to be a Vault"

As in the case of the Pareto front, this process is easiest to visualise in lower-dimensional space. Figure 2 illustrates a k-means clustering algorithm run on a two-dimensional data set as a collection of XY points. The iterative readjustment of the Voronoi bounding space according to subsequent containment tests for data points finally results in cells that describe boundary conditions easily identified by the eye as being optimally discretised.

K-means clustering is used extensively to find unknown relationships between data points in large data sets. Even though it is difficult to understand euclidean distances within data sets of high dimensionality in the abstract, clusters produced by such analyses -—so long as the data being used to structure them possesses useful descriptive capacities – generally makes intuitive sense when examining outcomes. For example, k-means clustering is regularly used in internet search engines for the purpose of clustering similar search elements together, where based on such data elements as key words and the geography



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linear variance
base point variance
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end radial variance
start radius
start radial variance
base point comparison
number of members
angular variance

of a story's origin, related content can be grouped together that can readily be grasped by an observer.

K-means clustering has been implemented in architectural models as drivers for fabrication rationalisation. A prominent example is the facade panelisation process developed by Gehry Technologies for the Soumaya Museum in Mexico City. This freeform structure's facade is comprised of more than 16,000 panels, each of which, in the original design geometry, is unique. However, by defining a maximum acceptable tolerance for each panel, the team was able to deploy the k-means algorithm to reduce the number of moulds required for fabrication to 49. More generally, the architects and engineers for Evolute software make use of k-means clustering in their plug-ins for facade panel rationalisation. For this experiment, k-means is not used to rationalise elements for fabrication, but in an entirely different capacity: to effectively understand, search, and discover the complex and varied design outputs that high-dimensional multi-objective optimisation algorithms produce.

Figure 4: (Opposite) Partial section of ten clusters

8.2.3 Simulation Systems

Spring-based particle simulations are frequently used in computational models for form finding and the integration of material behaviours into the design process. They use the same principles as agent-based models, with individual particles acting as agents, influencing each other according to definitions of connectivity and rules that define the consequence of interaction. Interestingly, they meet the explicit conditions that Mitchell details in his definition of a machine learning program: through the experience of their interaction with one another over time, simulation particles improve their performance at the task of describing material or behavioural consequences for their constituent elements.

Figure 5: (Opposite) selected 1:25 models

Figure 6: (Opposite) dashboard examining a single cluster, and its orientation within a solution set containing several passes of increasing cluster counts

Extensive research has been made regarding swarm intelligence and the effectiveness of encoding material capacities into simulation-based design models (Thomsen et al. 2010), but it is worth extending this frame of reference to consider the parallels that exist between such design systems and machine learning algorithms. This experiment relies on the use of material simulation for both form-finding and the production of evaluation objectives for the evolutionary algorithm.

8.3 Method

"Learning to be a Vault" (Figure 3) is set up to synthesise the modelling systems and considerations described above, including 1) a morphogenetic script capable of producing a wide variety of forms grounded in a tendency toward legibility, 2) a spring-based particle simulation for form-finding and loading behaviour of the actively-bent rattan member, 3) a multi-objective evolutionary solver for optimising the solution set and producing results on the Pareto front, and 4) a k-means clustering algorithm for searching the design space. The evaluation criteria for the experiment lies in the effectiveness of this integration, and the legibility, searchability and meaning inscribed by the final clusters.

8.3.1 Generation and optimisation

The morphogenetic script implements a recursive array of elements. There are two types of elements considered: primary members that attach both ends to the floor in an elastic arch, and secondary members that span between two primary members. Secondary members connect to primary members in two consecutive locations such that active-bending forces are interdependently shared between them. A number of transformations are available to primary and secondary elements through each recursion such that many forms of varying symmetry and spatial consequence are producible (Figure 5). Once formed, each collection is passed through a spring-based simulation engine (the Kangaroo plug-in for Grasshopper) to execute both form finding, and deflection under self-loading. Next, using a multi-objective optimisation solver (the Octopus plug-in), each collection is evaluated for suitability for continued breeding according to the following objectives: 1) minimal deflection, 2) restriction of tight, 3) targeted area covered, 4) targeted connectivity, and 5) targeted height for secondary members. Subsequent generations are then recursively passed through the same generative and evaluative process until suitable results have been produced.

8.3.2 Searching the design space

Based on this collection of objectives, over 80 generations more than 2000 unique Pareto optimised phenotypes are produced (Figure 4, 5). These phenotypes are then analysed according to series of descriptive paremeters developed by the designer. In this case, the descriptive parameters applied are a collection of numerical transformations of phenotype geometry. These are then passed through the software Octave (a numerical solver capable of rapidly executing complex machine learning algorithms) for computing the k-means algorithm and back into Grasshopper for visualisation and consideration of results.

Through an iterative implementation of this process, the designer uses both heuristics and intuition to identify further possible transformations to the ata that might result in improved clustering differentiation. In this case, 18 distinct numerically descriptive variables were developed, including: total materials used, average variance in height of secondary members, the radius of a circle inscribed in each primary member's start point, and the same for end points, and the distance variance between primary member base points. On their own, such parameters appear banal. However, when parsed through the clustering algorithm, they combine with one another to discretise a seemingly fragmented and intractably varied set of solutions into a collection of legible clusters.

It is here a new process of discovery emerges. Through the invention and application of these descriptive variables, one is able to steer the intrinsic relationships between relatively simple aspects of the geometry's underlying data structures toward a coherent and easily searched design space. This process of iteration is critical and effectively operates as a second stage for design execution. The clustering of suitably large collections of phenotypes – particularly those that have been optimised for a variety of objectives – may ultimately result in a form of speciation, wherein the designer is able to identify highly distinct solutions that may be suitable for diverse architectural applications.

The development of effective data visualisation tools is essential for managing the information about clusters that is produced. One measure for determining the efficacy of a clustering analysis is the average variance for all variables of each constituent data point relative to its cluster centroid. Here, a smaller variance indicates clusters that better describe their constituent data points. As such, a zero variance requires that there be exactly one cluster per data point. This would offer no simplification, and therefore the purpose of the process is for the designer to establish a threshold that effectively finds the least (and most searchable) number of clusters that retain a high level of descriptive capacity. For this experiment, a dashboard is developed that allows for the designer to rapidly understand the dynamics of different clustering passes, with each incremental pass adding another descriptive cluster. The dashboard indicates how adding numbers of clusters from one pass to the next decreases variance for the entire solution, but does so at a decreasing rate, and at the expense of searchability. To facilitate finding an effective threshold, it allows for the designer to select individual clusters, see the individual phenotype most representative of the cluster centroid, read the relative average values of the descriptors used for executing the algorithm, and see which clusters are similar to it both within the same clustering pass and in those both preceding and subsequent to it (Figure 6).

8.4 Discussion

Increased computing power and a proliferation of tools make more advanced multi-objective optimisation design models more tractable and create a need for new methods for managing phenotype outputs emerges. Attendant to having more complex collections of objectives is a higher volume of outputs. So not only does this make it difficult to visualise these outcomes on the Pareto front, but the sheer number of phenotypes to be processed makes a case-by-case review difficult. This experiment represents a first look at applying unsupervised learning algorithms for the purpose of organising such high-dimensional data output into coherent segments and as a result enabling the designer to engage in a secondary operation of discovery through the development of descriptive parameters that steer this segmentation process.

There are a number of opportunities to further refine and enhance the utility of the approach presented here. First of all, applying the clustering algorithm between generations in the evolutionary solver would enable the designer to implement a form of directed breeding, with non-desirable clusters removed from the pool of available solutions. This would more tightly couple the different contributing model elements and lend a higher degree of control to the designer. Also, there are multiple approaches for numerically processing descriptive features to heighten their ability to produce better distinguished clusters, as well as for identifying thresholds for ideal number of clusters for a given data set. These approaches can be further explored and implemented.

8.4.1 Conclusions

Machine learning algorithms present a number of opportunities for the enhancement of computational design practice. There are varying degrees of maturity between different methods currently applied. For example, while the use of evolutionary algorithms in the design sciences has an established history and advanced epistemology, algorithms such as k-means clustering have had more limited application. Neural networks of multiple type have been deployed. “Growing Neural Gas” networks have been implemented for the development of use and occupation analysis in urban environments, and have been deployed for developing way-finding analyses for space plans at multiple scales (Langley et al. 2007). Backward propagating neural networks have been used to drive robotic instruction for resilient structural systems (Mehanna 2013). Computational designers have long applied spring-based particle and agent-based simulation systems in their models, which can be seen to exhibit functional equivalence to machine learning models, but for problems particularly well-suited to the design sciences.

Machine learning models designed to handle the most difficult problems are often conceived of and constructed as a complex of multiple distinct approaches, operating in some combination of parallel and sequential synthesis (Flach 2012). In addition to the operational benefit of using machine learning algorithms directly to enhance the design capacities of their models, such an outcome should be compounded through the conception of their models as inter-scalar ecologies of such knowledge-acquiring algorithms.

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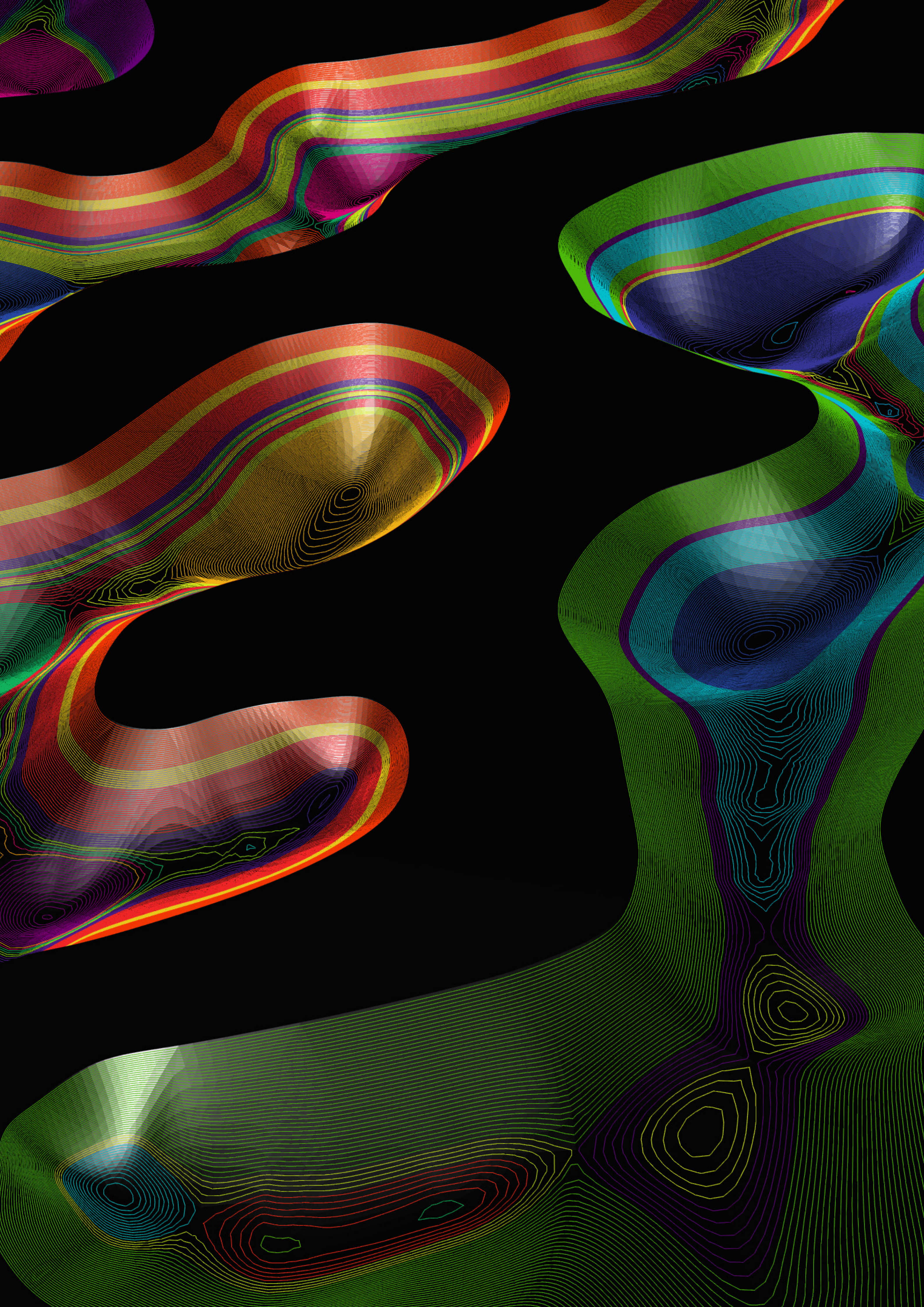
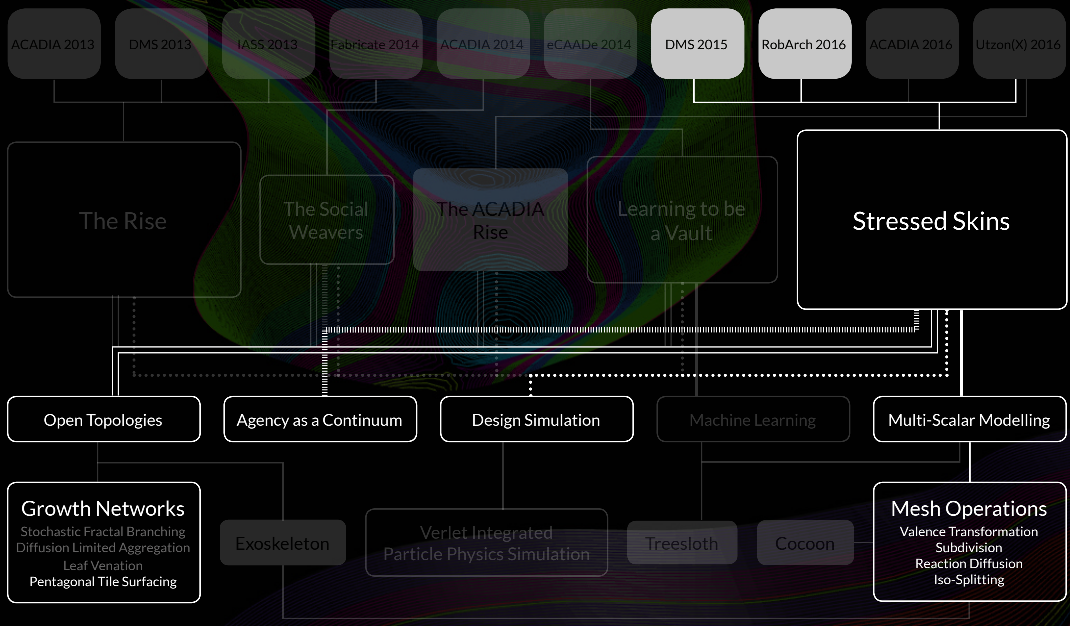




Publications V: Stressed Skins

The sixth and seventh publications are here presented for their examination of the research experiment *Stressed Skins*.

> Nicholas, P., Stasiuk, D., Nørgaard, E. C., Hutchinson, C., & Thomsen, M. R. (2015). *A multiscale adaptive mesh refinement approach to architectured steel specification in the design of a frameless stressed skin structure*. In Proceedings of The Design Modelling Symposium 2015: Modelling Behaviour (pp. 17-34). Springer, Cham.

> Nicholas, P., Stasiuk, D., Nørgaard, E., Hutchinson, C., & Thomsen, M. R. (2016). *An Integrated Modelling and Toolpathing Approach for a Frameless Stressed Skin Structure, Fabricated Using Robotic Incremental Sheet Forming*. In Proceedings for Robotic Fabrication in Architecture, Art and Desgin 2016 (pp. 62-77). Springer, Cham.

Engaging in Multi-Scalar Modelling

Stressed Skins was both the final and most significant experimental project undertaken as part of my research project. Again relying on both open topologies and design simulation as a base framework for activating the parameter space, *Stressed Skins* extended a focus in multi-scalar modelling as a line of inquiry in adaptive parameterisation. Multi-scalar modelling is an approach to describing a target system of interest through the simulation of its behaviours in conjunction with one another at multiple scales of resolution. This requires the implementation of bi-directional constraints to parameterise discrete descriptive systems that are either applicable or tractable at different levels of focus or resolution. This requirement for the explicit definition of parametric interfaces between discrete modelling environments makes multi-scalar modelling a productive framework for the exploration and implementation of partial model networks that exhibit holistic performance characteristics and increasing potentials for being activated and improved through the use of adaptive parameterisation techniques.

Collaboration

Stressed Skins reflects the continued consideration of collaboration as essential to the effective formulation and application of adaptive parameterisation in complex, partial model networks. The aim to more effectively coordinate and manage multiple design and research interests provides an ideal framework for exploring how the formulation of dynamic parameter spaces between partial models can improve their representational potential and flexibility in interfacing with one another. *Stressed Skins* reflected a deep interest by other collaborators in incremental sheet metal forming as a fabrication technique and means to more directly interface with and program customised material properties. This interest demanded a great deal of physical prototyping and custom physical tooling, which was developed both parallel to and in conjunction with the multiple digital instruments applied throughout the design, development, and final fabrication processes. The formulation of digital models whose underlying data structure would enable not only the transfer of critical data across scalar thresholds during design and analysis phases, but would also extend into and inform the CNC-driven fabrication process developed or maintained by collaborators remained paramount.

While both papers presented here present *Stressed Skins* as an overall project, each has its own particular focus. The first examines more closely the network of partial models used in the development of the project, discussing the use of half-edge meshes to manage a holistic process of design, analysis, and delivery through multiple but interdependent representational engines. The second more closely examines the robotic fabrication processes employed in the production of the final demonstrator, which helps describe how persistent, but adaptive data structures or substrates confer great potential not only for enabling complex simulation-based or algorithmic transformations that increase design intelligence, but critically also feed forward into the production phase of complex architectural projects.

Project role

In addition to my being the principal developer of the modelling systems used throughout the project – including in design probes, custom digital instrumentation, generative logics, and many fabrication drivers – I also closely collaborated in the project's conceptual formulation, its design, the development and testing of physical prototypes, and installation.

Author role

My contribution to these publications is extensive. I authored the technical portions of each paper that focus on the modelling systems used for the design, development, and analysis of *Stressed Skins*. This work extends into discussion of how the design and development model both directly inform and interface with the models used to drive fabrication. I also worked in close coordination on the portions of the text that present and reflect on the theoretical frameworks concerning motivation, research questions, and findings.

Presentation

The papers presented here have been reformatted for continuity, but all textual and visual content remains unaltered from its original, peer-reviewed presentation.

9. A multiscale adaptive mesh refinement approach to architectured steel specification in the design of a frameless stressed skin structure

Reformatted from: Nicholas, P., Stasiuk, D., Nørgaard, E. C., Hutchinson, C., & Thomsen, M. R. (2015). *A multiscale adaptive mesh refinement approach to architectured steel specification in the design of a frameless stressed skin structure.* In Proceedings of The Design Modelling Symposium 2015: Modelling Behaviour (pp. 17-34). Springer, Cham.

Abstract

This paper describes the development of a modelling approach for the design and fabrication of an incrementally formed, stressed skin metal structure. The term incremental forming refers to a progression of localised plastic deformation to impart 3D form onto a 2D metal sheet, directly from 3D design data. A brief introduction presents this fabrication concept, as well as the context of structures whose skin plays a significant structural role. Existing research into ISF privileges either the control of forming parameters to minimise geometric deviation, or the more accurate measurement of the impact of the forming process at the scale of the grain. But to enhance structural performance for architectural applications requires that both aspects are considered synthetically. We demonstrate a mesh-based approach that incorporates critical parameters at the scales of structure, element and material. Adaptive mesh refinement is used to support localised variance in resolution and information flow across

these scales. The adaptation of mesh resolution is linked to structural analysis, panelisation, local geometric formation, connectivity, and the calculation of forming strains and material thinning.

9.1 Introduction

The research structure Stressed Skins investigates the highly integrated material and formal specification of an inexpensive, long-standing architectural material best known for its homogeneity: steel. In this paper, we describe the process of asymmetric incremental sheet forming (ISF). We link ISF process parameters to variable specification at three architectural scales: within the material, cold working increases the strength; within the panel, forming out of plane increases the local stiffness of the sheet; within the structure, overall rigidity is obtained and increased in relation to panel locations, and where geometric formations on one side of the stressed skin connects with geometric formations on the other. We introduce a computational modelling approach for operationalising these relations, based on the use of an adaptive, unstructured mesh that instrumentalises inter-scalar feedback during the simulation process.

9.2 ISF process

Incremental sheet forming (ISF) is an innovative fabrication method for imparting 3D form on a 2D metal sheet, directly informed by a 3D CAD model. In the ISF process, a simple tool moves over the surface of a thin (0.5-1mm) metal sheet so as to cause localized plastic deformation (Fig.1) (Jeswiet et al. 2005). ISF is of interest for three major reasons: it avoids the need for a costly, die (negative forming), by instead directly machining semifinished pieces of metal. Secondly, because forming is highly localized, the force required does not increase with scale, meaning that there is theoretically no limit to the size of the sheet that is formed (Tisza 2012). Lastly, ISF has been shown to extend the formability of metals beyond what is achievable via conventional forming via stamping or deep drawing (Bagudanch et al. 2013).

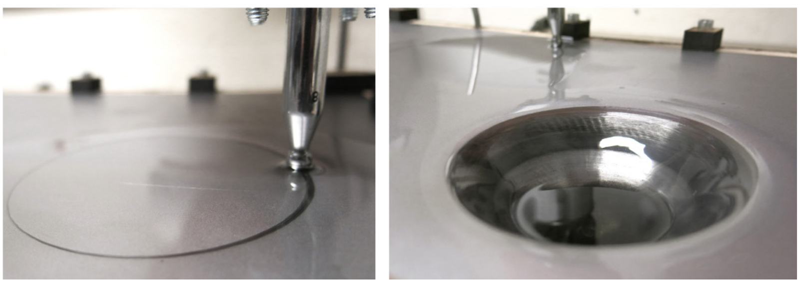


Figure 1: Single point incremental forming.

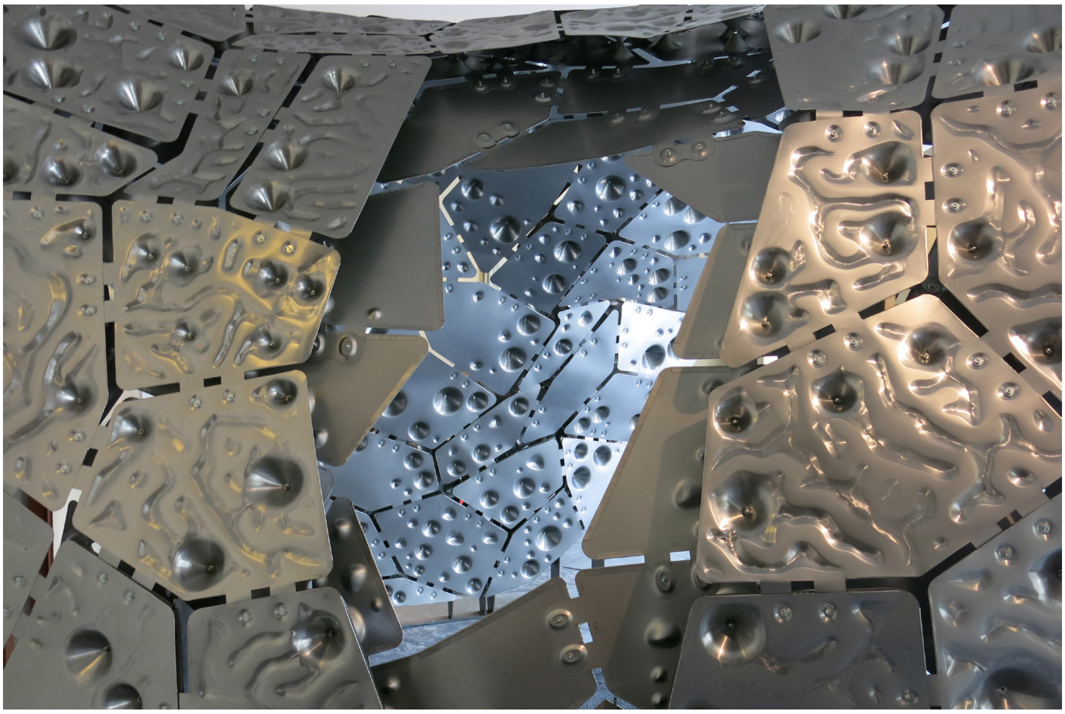


Figure 2: The *Stressed Skins* installation at the Danish Design Museum.

New research in this field examines scaling up the process: Ford and Boeing aim towards a system with an effective work area of 2.0 meters x 1.5 meters (Energy 2015).

Transferred into architecture, ISF moves from a prototyping technology to a production technology. Within the context of mass customisation, it provides an alternate technology through which to incorporate, exploit and vary material capacities within the elements that make up a building system. Potential architectural applications have been identified in folded plate thin metal sheet structures (Trautz and Herkrath 2009) and customised load-adapted architectural designs (Kalo and Newsum 2014, Br¨uninghaus, Krewet, and Kuhlenk¨otter 2013). Recent research has established ISF as structurally feasible at this scale (Bailly et al 2014), and explored the utilisation of forming cone geometries as means to reach from one skin to another (Kalo and Newsum 2014, Bailly et al. 2015)

9.3 Stressed skin structures

In this research, the ISF process is used to fabricate a stressed skin structure. Stressed skin structures are thin sheet structures in which the skin is structurally active, bearing a considerable part of the load and providing significant rigidity. They are an intermediate between monocoque and rigid frame approaches, and have been particularly associated with light weight structures. In their design, rigidity is a central concern. One of the main problems is to ensure rigidity at multiple scales: against the instability of the whole structure and also the local buckling of the parts which have to carry compressive load. Stressed Skins develops a structural approach in which the skin carries planar and shear forces, without an additional framing system, at the scale of a pavilion. Local corrugation avoids buckling through geometric stiffening of the skin, while shear connectors transfer loads between upper and lower skins to rigidise the entire structure (Fig.2). These features, as well as all in-plane connections, and shear connections between the upper and lower skin, are achieved through the deformation of the skin and are outcomes of the computational modelling process.

9.4 Research objective: a mesh-based approach to communication across scales

The object of this study is to explore how a mesh can work as a substrate for enacting and communicating various types of analysis across multiple scales to support the geometric specification, structural simulation and fabrication of a stressed skin structure. There are two established mesh-based methods for adapting resolution where required to capture complex dynamics, small scale geometry and scale sensitive calculations: the nesting of structured grids (multiple contiguous domains) and the adaptation of a non-structured grid (a single continuous domain). The research begins with the aim to deploy a single, continuous-domain multi-scale mesh as an exclusive design medium for negotiating the form-finding and analysis, and producing all relevant outputs for fabrication and representation. This is ultimately achieved, however, via a hybrid approach that implements both contiguous and continuous approaches.

9.5 Modelling framework

The modelling framework for Stressed Skins considers macro, meso and micro scales as markers along a continuum describing variable, interdependent functionalities within the design system (Fig. 3). In general the macro scale encompasses the resolution of global design goals, overall geometric configurations, and a full-scale understanding of structural performance. The meso scale considers the project at an assembly and sub-assembly level, and is concerned with material behaviours tied to geometric transformation, detailing and component-level tectonic expression. The micro scale is concerned with

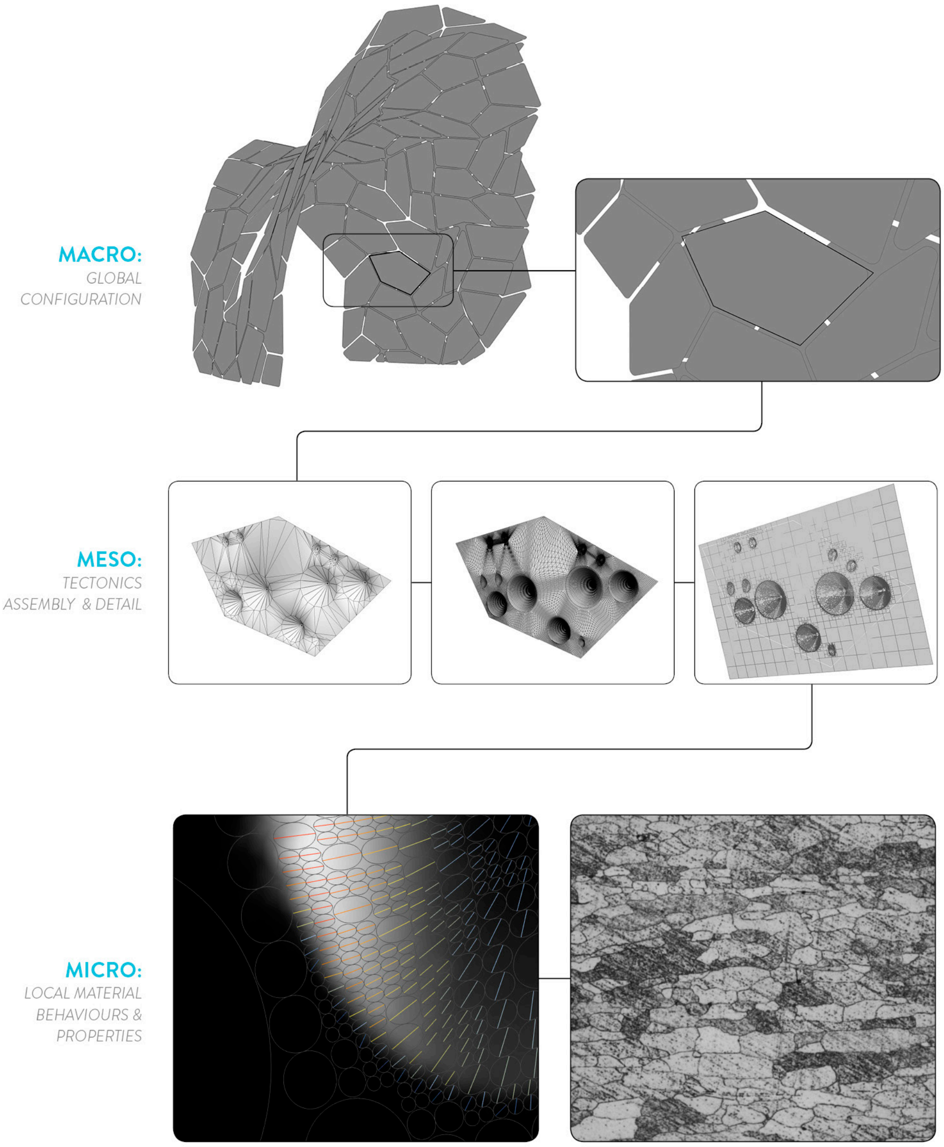


Figure 3: Multiscale considerations in *Stressed Skins*.

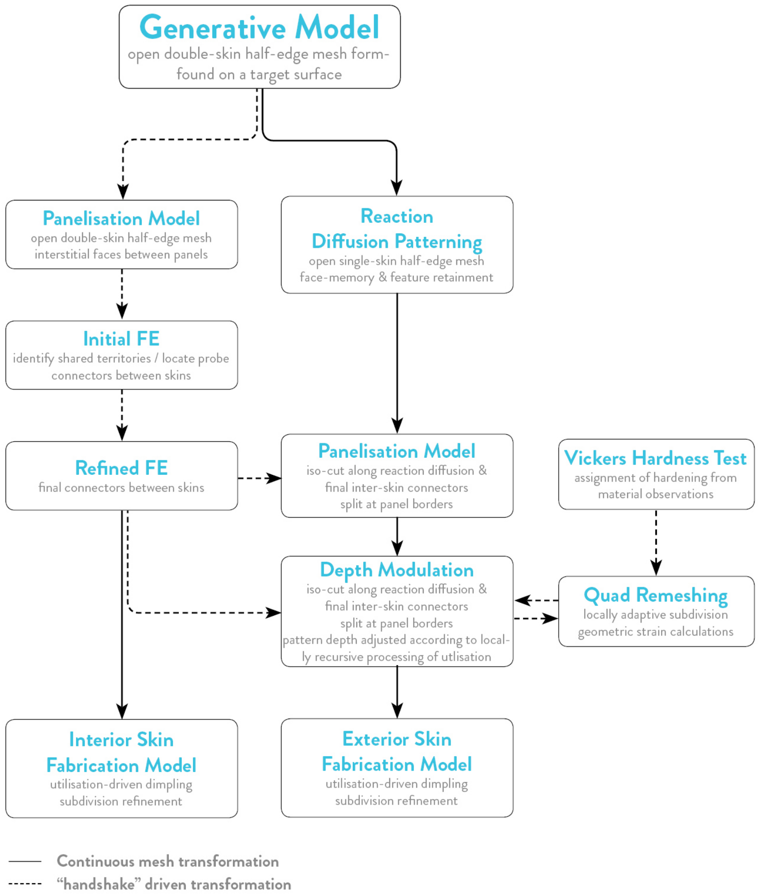


Figure 4: Networked model dependencies.

relevant material characteristics at the most discretised level. The multi-scale modelling approach used here is then comprised of those techniques which enable the information generated at each of these markers to flow both up and down the continuum.

9.5.1 Strategy and computational tooling

These modelling parameters are organised using a half-edge (or directed-edge) mesh data structure (Campagna, Kobbelt, and Seidel 1998). Half-edge meshes enable the deployment of n-gon faces (rather than more standard triangulated or quadrilateral faces). This opens up the possibility for designing with more complex topologies. In this case, a pentagonal tiling algorithm was used, resulting in a base mesh comprised of five-sided faces. The features of this mesh – such as its vertices, half-edges and faces – are coupled with a series of lists, dictionaries and Grasshopper data trees that effectively bundle within mesh elements critical design data related to: topology, form-finding and geometry; structural behaviour; material characteristics; connection detailing; and patterning and tectonic expression. (Fig. 4)

The primary digital design instruments used are Rhino and Grasshopper as a base modelling environment, the Plankton library for scripting half-edge meshes, a beta library of the Kangaroo2 physics engine for form finding, and Karamba for finite element analysis. A series of bespoke tools and implementations are created for managing and modifying the design meshes. These operate such that the meshes are transformed to operate at scales appropriate to particular function – or, when necessary, handshake with other meshes – while retaining the integrity of these key relationships and informing the design with new relevant data.

9.5.2 Macro Scale I

Preconfiguration

The configuration of the overall form is developed through a multistage modelling process. The first stage entails the top-down drawing of a single target design surface in response to constraints introduced by the site and in pursuit of specific design ambitions. This small site – the foyer of the Danish Design Museum – requires the maintenance of adequate open circulation along its two primary axes and through two additional doors. The design ambitions lie in producing an asymmetrical, cantilevered form that will help test the forming limits of the steel, its capacity for geometric adaptation, and its structural performance (Fig. 5).

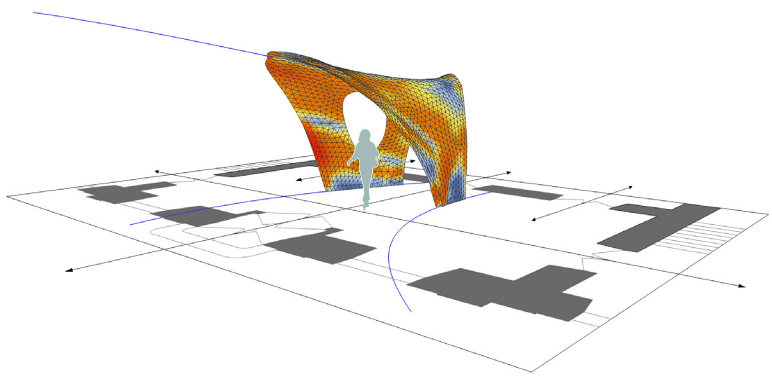


Figure 5: Target design meshes for upper and lower skin, deployed in response to circulation constraints and with the ambition to produce an asymmetrical, cantilevered form. Variable thickness between the skins is determined by a simple FE analysis on the base mesh.

With this surface form established, a shell finite element analysis is performed, loaded under self-weight. Utilisation of shell elements resulting from this analysis are used to drive locally varying offsets from this single surface into two discrete target surfaces, one for the upper and one for the lower skin. Higher utilisations result in greater target depth between the two skins.

Figure 6: (Opposte) Panelisation based on pentagonal tiling realised through a halfedge mesh. Planar geometry defined from generative form finding enables precise offsets, and order of formation and embedded topology simply organises male/ female connection details.

Figure 7: (Opposte) Identification of "shared territories" between panels on the upper and lower skins, and the establishment of a single "probe connection" within each.

Figure 8: (Opposte) Geometric definition of each probe connection, and extraction of shear forces at each connection point through an initial FE analysis.

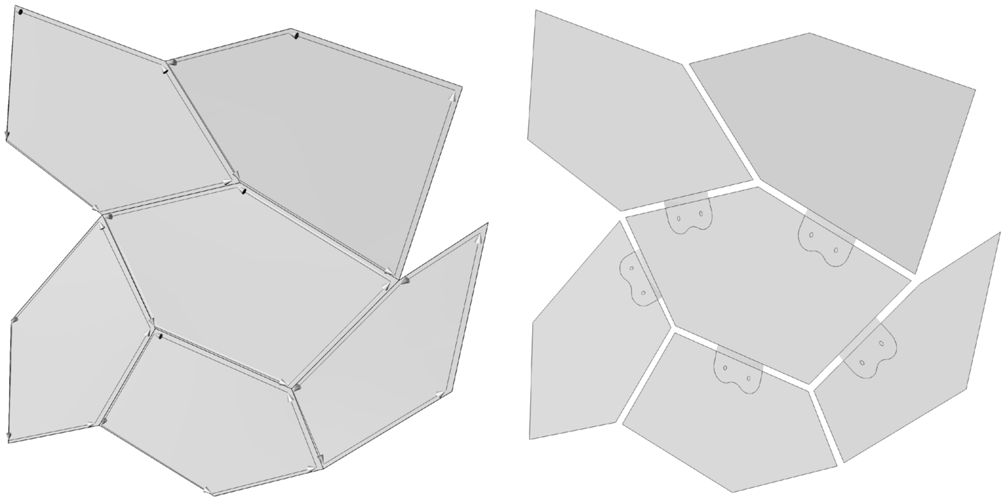
Generative Model

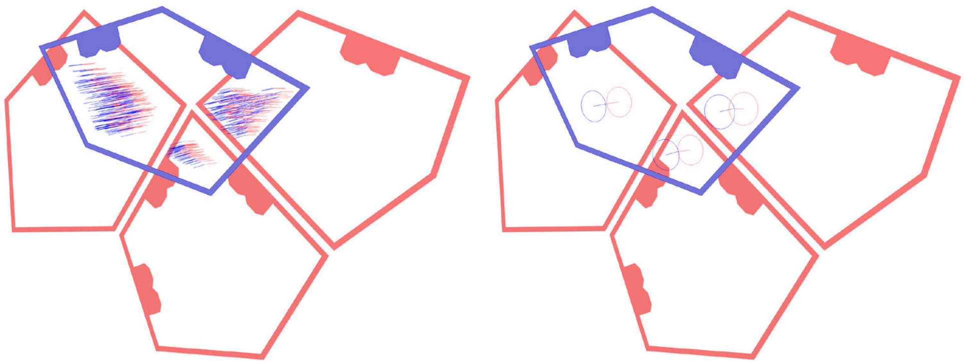
The two skins are then grown on each of these offset target surfaces by sequentially locating pentagonal panels, spiraling outward from a seed tile on each surface. The Kangaroo2 physics engine is a constraint (or goal) based form-finding and simulation design system. In addition to pre-configured goals embedded in the library, the scripting interface enables the coding of custom goals. The recursive form-finding employed here includes edge length and angle goals, which seek to maintain the ideal geometry prescribed by the planar tiling rule set. Target mesh pulling goals draw the mesh vertices out of plane and to the target surfaces. As each new panel is located in the assembly, the solver reconciles these geometrically competing interests into a configuration that retains the topology of the tiling strategy but minimally adapts its emerging form to approximate the target surface. Additional goals include: vertex repelling goals between the upper and lower skins that increase diversity in connectivity between them; goals that neither skin collide with the other; and finally, after the target surfaces are fully tiled, a planarising goal is introduced to the panels. This last goal is essential to make fabrication viable, and further deforms each panel from its ideal planar geometry. Throughout this generative process, all relevant data between the form-finding solver and the mesh topology are coordinated as a unified data structure.

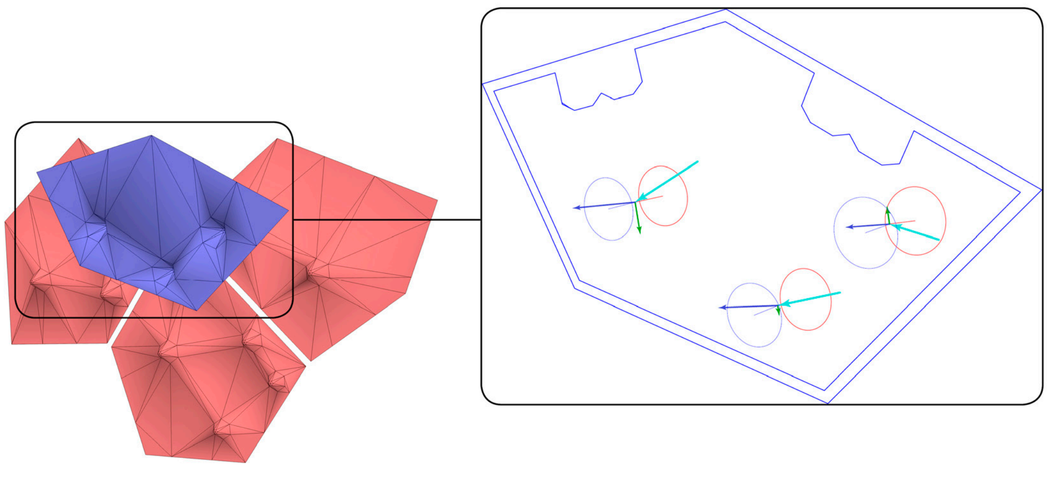
Panelisation Model

This pentagonal mesh then directly folds into a new, hybridised mesh that incorporates panel offsets for the geometric definition of boundaries, and specifies the connection detail between panels on the same skin. This consists of a male element on one panel and a female element on its adjacent panel. This male/female relationship is determined for each edge according to the generative sequence of each panel, such that older panels reach out with the male connection. This base model provides the specifications necessary for laser cutting the profiles – or dies – for each panel. A simple etched labelling strategy allows topological information to directly activate a self-jigging assembly approach during installation. (Fig. 6)

Simultaneously, connective faces within the design mesh are produced to bridge the gap between the newly offset panels. This supported topological consistency in the mesh and is subsequently key to the production of a finite element analysis mesh. Fabrication requires a minimum offset from the panel edges, as well as from the connection details. Based on the knowledge of these geometrical constraints, formable regions called "search boundaries" are then







identified within each offset panel.

From these search boundaries, "shared territories" are identified between proximate panels on the lower and upper skins. This secondary form-finding procedure is comprised of a custom, iterative process whereby lines drawn normal to planes from opposite panels self-orient such that they each intersects at a point, with the requirement that the base of the cones defined by each potential connection fall within the search boundaries on both panels. These are derived from a large number of initial samples "feelers" from each panel which identify proximate feelers from panels on the opposite skin, and which dynamically relax within each panel's shared territory and search boundary. As a result many such many potential connection points are identified within each shared territory.

Initial FE Model

Once these territories and their constituent connection points are identified, the most central, or average, connection point is established for a single "probe connection" (Fig. 7). The conical geometries for connections between skins are integrated with the panels and connective faces – again along with inherited data structures from previous efforts – into a coarse triangulated mesh on which a finite element analysis is performed. The resulting modelling method relies on a hybrid of beam and shell elements, which in addition to data on nodal translations and rotations produces readings of shear forces at connection points between the skins, and utilisations and bending forces within the panels (Fig. 8).

9.5.3 Meso Scale

Refined FE Model

The results from this initial FE and the previously solved connection points within each shared territory synthesise into a refined FE model. For this it is asserted that each territory have at least one connection, and each panel – where possible – have at least three connections. Based on both of these

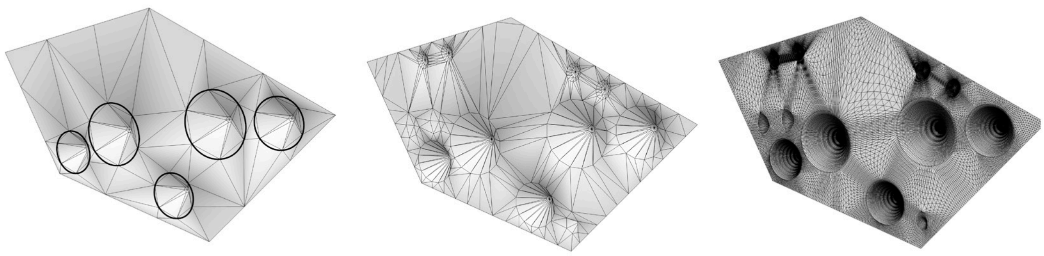


Figure 9: (left to right) a. Redistribution of connections between skins based on improving resistance to shears identified in the initial FE analysis, b. strategic dimpling of panel as a tectonic response to in-panel utilisations, c. direct subdivision refinement for production of fabrication model.

interests, panels range in connection count from 0 to 5. The goal here is to maximise the diversity of panels connecting with each other across the skins in an effort to prevent possible hinging and maximise triangulation across skins each panel. When multiple connection points are allocated within a shared territory, they are aligned to configure perpendicular to shear forces in the initial models corresponding probe connection (Fig. 9).

Strategic Dimpling and Lower Skin Fabrication Model

This refined FE model is subjected to another analysis which directly drives the tectonic patterning of the lower skin. For this, utilisation forces within each panel are used to drive tectonics and improve performance through the forming of a responsive pattern of oriented dimples within the structure. This pattern is located in areas of high utilisation and bending energy, the former of which is locally reduced through the strain hardening of the material and the latter better managed through the geometric stiffening resulting from the dimples. Shear forces within nearby connections orient the dimples, and enhance the structural expression of the pattern.

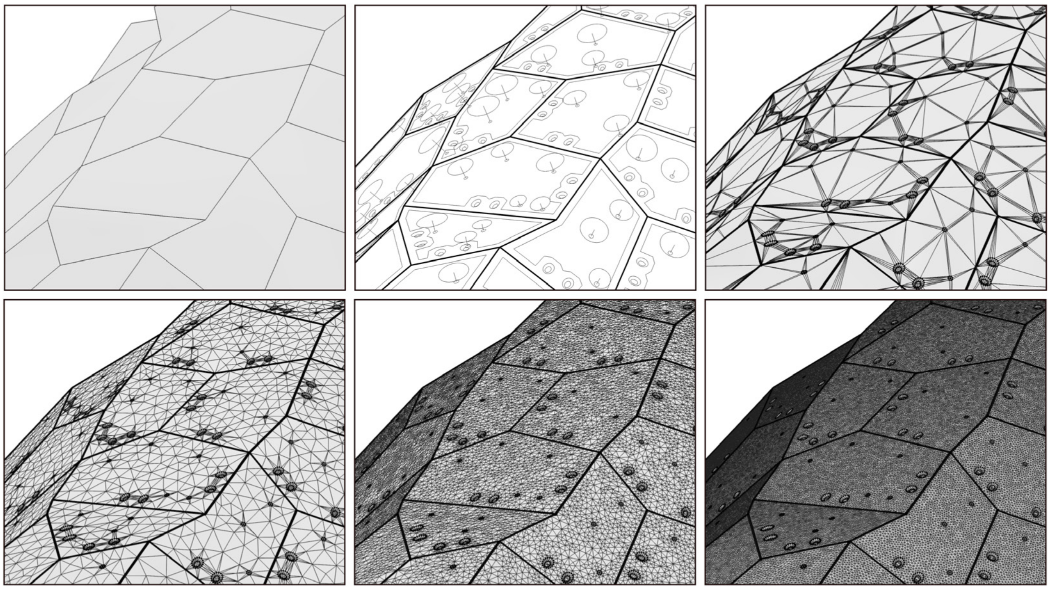
A final lower skin fabrication model is then synthesised from the refined FE model and the resulting dimple pattern, and subdivided to a higher resolution for fabrication, each panel systematically arrayed for extracting toolpaths.

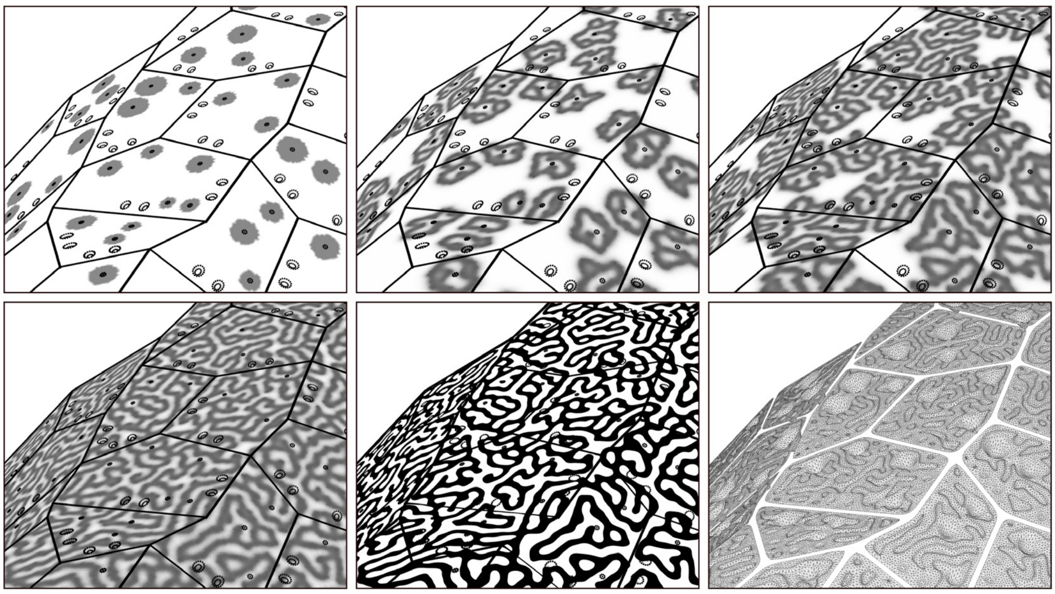
9.5.4 Macro Scale II

Reaction Diffusion

The foundation for the patterning strategy on the upper skin is the implementation of a Gray-Scott reaction-diffusion algorithm (comprised of the virtual ingredients U and V). This is executed on a higher-resolution, topologically persistent triangulated subdivision of the original generative pentagonal tile mesh, and informed with fixed vertex locations for connection elements that later enable the instantiation of precise connection geometries. The goal here is to produce a pattern on the upper surface whose isotropic nature assists in stiffening panels without favouring any particular directionality.

The subdivision technique used here allows for newly introduced features to inherit key data elements during both decimation and subdivision. It is an extension of a remeshing script developed by Daniel Piker, which itself allows for the specification of fixed geometric features during these operations as well (Fig. 10) . The mesh was then further discretised according to a surface-level iso cut, which split faces along edges according to the reaction-diffusion U and





V ingredient parameters at each vertex. The areas inside the iso surface were considered formable (Fig. 11).

9.5.5 Meso to Micro Scale

Variable Resolution Quad Mesh

The meshing technique deployed here is an adaptive, variable resolution square mesh. This quad mesh is mapped onto an existing plane at a coarse resolution, starting from the panel plane. The vertices for each quad face are projected to the target geometry, and the face is tested for planarity. If the face is within a set tolerance, it remains at its current resolution. If it is not, it subdivides into four faces. This test is recursively applied to the mesh such that it locally adapts its resolution to relevant geometric features. After several iterations, each quad can be understood both in its initial unformed square state on the starting plane, and in its strained quad state resulting from geometric forming. A circle inscribed in the initial square is then projected onto the deformed quad, resulting in an ellipse whose primary and secondary axes produce both direction and lengths of strains resulting from the forming process (Fig. 12) (Emmens and Boogaard 2007). Strains are calculated as true strains (Eq.1)

$$(1)\quad \varepsilon True = \ln(L0 \times L1)$$

The resulting thickness strain (ε3) is determined by volume constancy (Eq. 2)

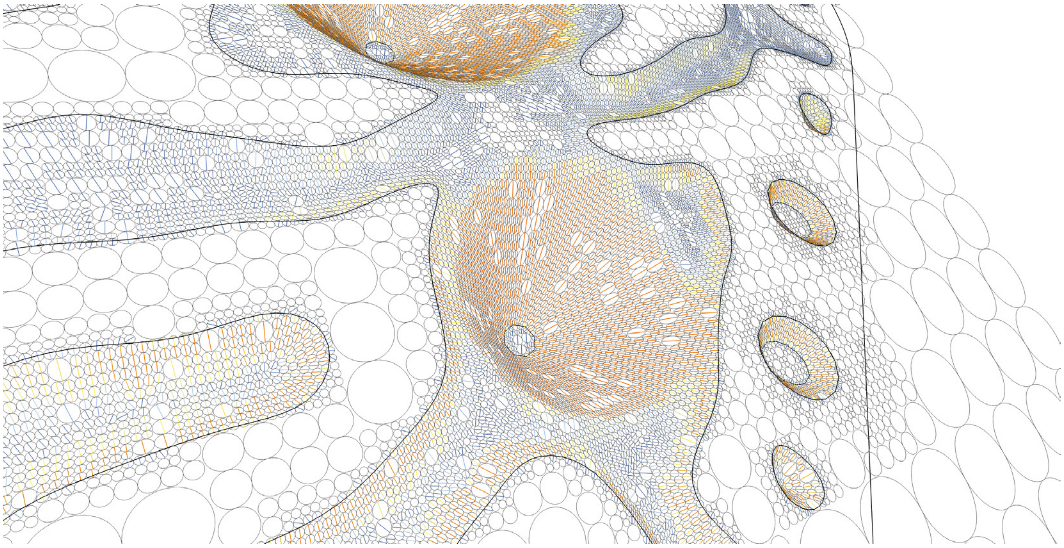
$$(2)\quad \varepsilon 1 + \varepsilon 2 + \varepsilon 3 = 0$$

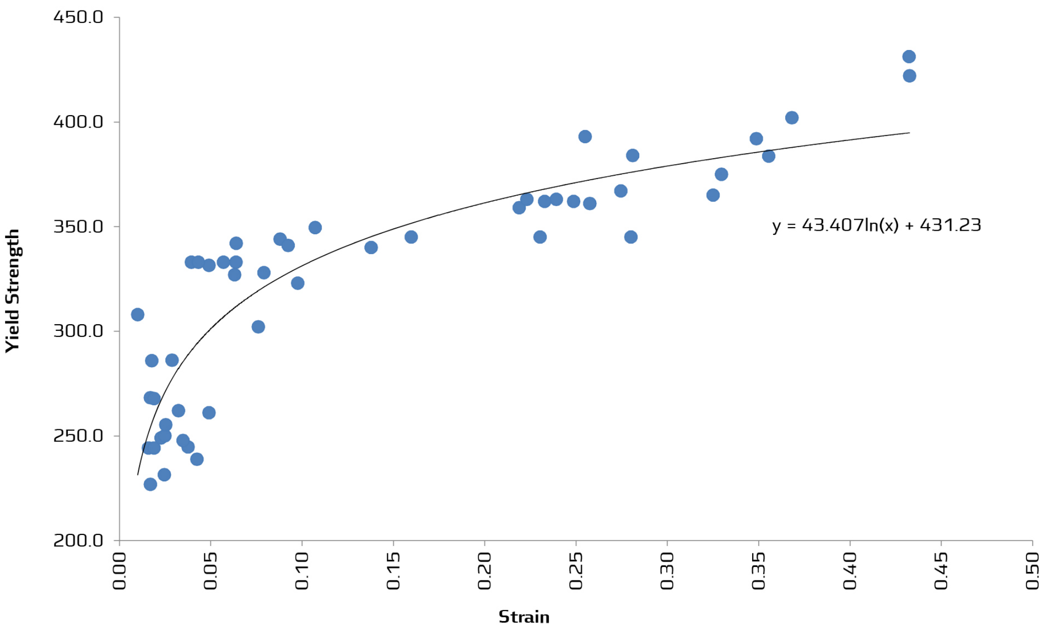
Calibrating Micro Scale Calculations using Vickers Hardness and Optical Microscopy

To calibrate and verify the prediction of local strains, and to relate this to increase in yield strength, a series of empirical tests are made on material samples that vary processing parameters in a systematic fashion. To best incorporate all processing variables, all samples are produced using the same rig as used for final production. The local increase in strength is monitored using Vickers hardness tests with a 5kg load measured on the cross sectional thickness of the sheet. Measurements are made along the cross-sectional length of a formed component and the resulting hardnesses are converted to estimated flow stresses and correlated with the local strains. Fig.13 shows a graph charting the observed relationship between local strains induced by

Figure 10: (Opposite) (left to right, top to bottom) a. Unrefined upper skin pentagonal mesh, b. location of features for connections between panels within upper skin, as well as between upper and lower skin, c. introduction of features into pentagonal mesh as triangulated elements, d. through f. subdivision of mesh to resolution required for executing reaction diffusion patterning scheme at desired resolution, while retaining key features both geometrically and topologically.

Figure 11: (Opposite) (left to right, top to bottom) a. Initialisation of reaction diffusion algorithm on subdivided mesh, b. through d. pattern generation on the mesh, with values represented as colour gradient, e. iso-splitting of pattern for sharp discretisation of formable areas, f. Integration of connections between skins with pattern array.





450.0
400.0
350.0
300.0
250.0
200.0
Yield Strength
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
0.45
0.50
Strain
y = 43.407ln(x) + 431.23

forming and the measured flow stress calculated from the Vickers hardness measurements.

9.5.6 Micro to Meso Scale

Figure 12: (Opposite) Quad recursively remeshed to adapt through subdivision in order to more precisely describe geometric features. Circles inscribed in each quad are projected from the plane onto the mesh. Here deformation is read in the long axis of ellipses that have been deformed through projection. Flat areas on the mesh reflect unformed areas.

Depth Modulation and Upper Skin Fabrication Model

The modelling strategy for modulating the pattern depth on the upper skin results from the synthesis of several of these modelling systems. It relies on knowledge of connection geometries and formable areas for activating the reaction diffusion pattern within each panel; nodal translations and rotations at connection points both within and between skins from the refined, global FE analysis; and the capacity to locally calculate granular material properties through the adaptive quad mesh and the measured flow stress.

The process begins by discretising each panel from the reaction diffusion model, applying the geometry of the connection elements, and leaving the rest of the panel "unformed". This minimum forming baseline geometry is then further subdivided into individual, triangulated elements, each of which is capable of having unique material properties assigned to it in the Karamba finite element modelling environment. An analysis is performed on each face, with extracted local strains from the adaptive quad remeshing technique described above. Resulting yield strengths for each face are specified by the measured relationship between strain and yield strength.

Figure 13: (Opposite) Observed relationship between local strains induced by forming and measured flow stress calculated from the Vickers hardness measurements.

Using Karamba's prescribed displacements enables the process of subjecting this locally informed mesh to corresponding nodal rotations and translations along its connection points, as extracted from the refined FE model. By virtually working the panel in this way, the depth of each panel is incrementally and locally modulated. Here, vertices in the prescribed patterned area respond to proximity to faces that are heavily utilised when subjected to the prescribed displacement. Through an iterative accumulation of change in depth (Fig. 14) – and iterative analysis and application of resulting local changes in yield strength due to strain hardening (Figs. 15 & 16) – the patterning emerges as a tectonic response to utilisation and bending energies introduced by the global structural conditions.

Following this iterative introduction of locally adaptive depth within channels defined by the reaction diffusion patterning, the mesh is subdivided to a higher resolution for fabrication, arrayed by panel toolpath extraction.

9.6 Fabrication and Toolpathing

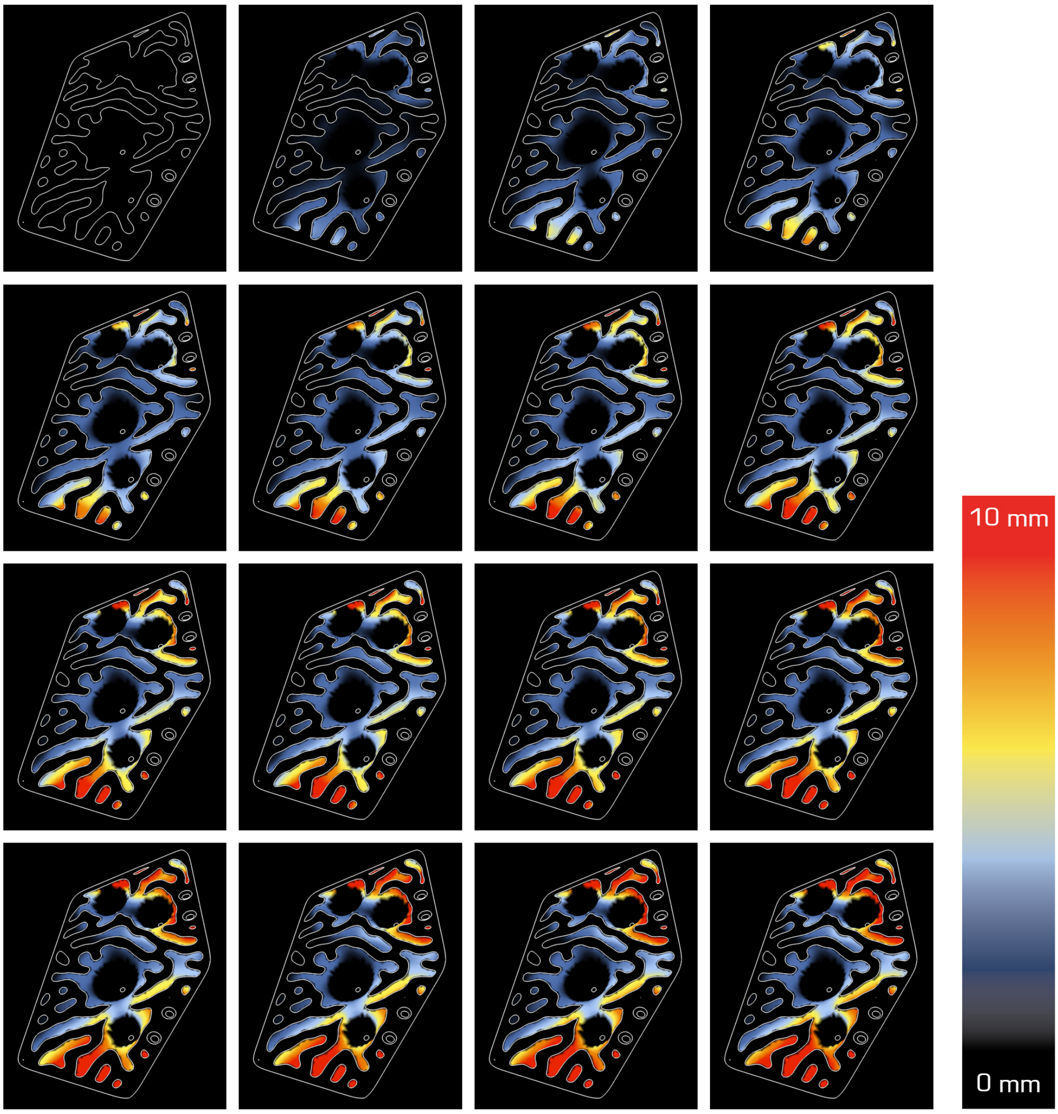


Figure 14: Depth modulation of patterning introduced iteratively. The incremental increase in depth from a minimum offset. Here black represents areas that remain planar or are fixed at a depth required for connections, and coloured areas reflect formable areas iteratively deepening in response to local utilisations.

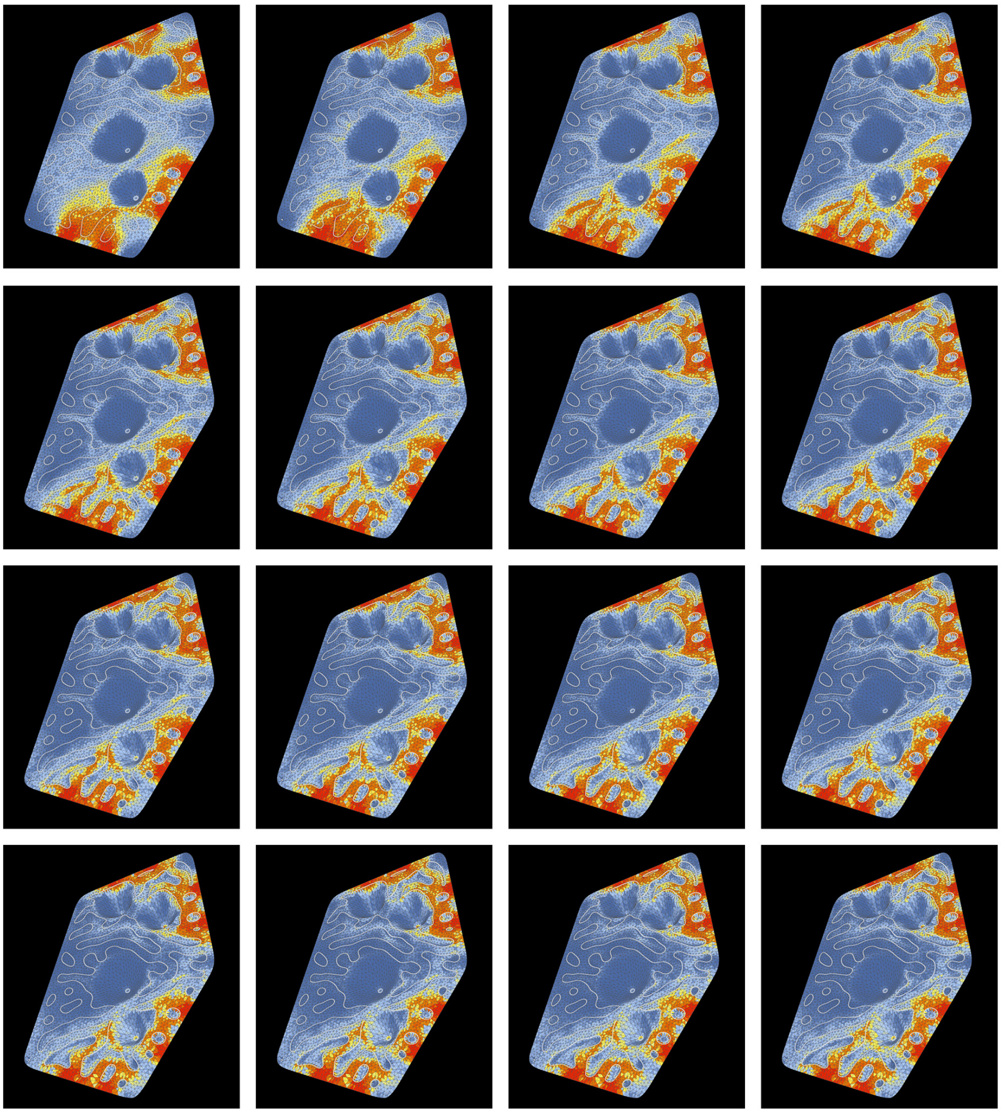
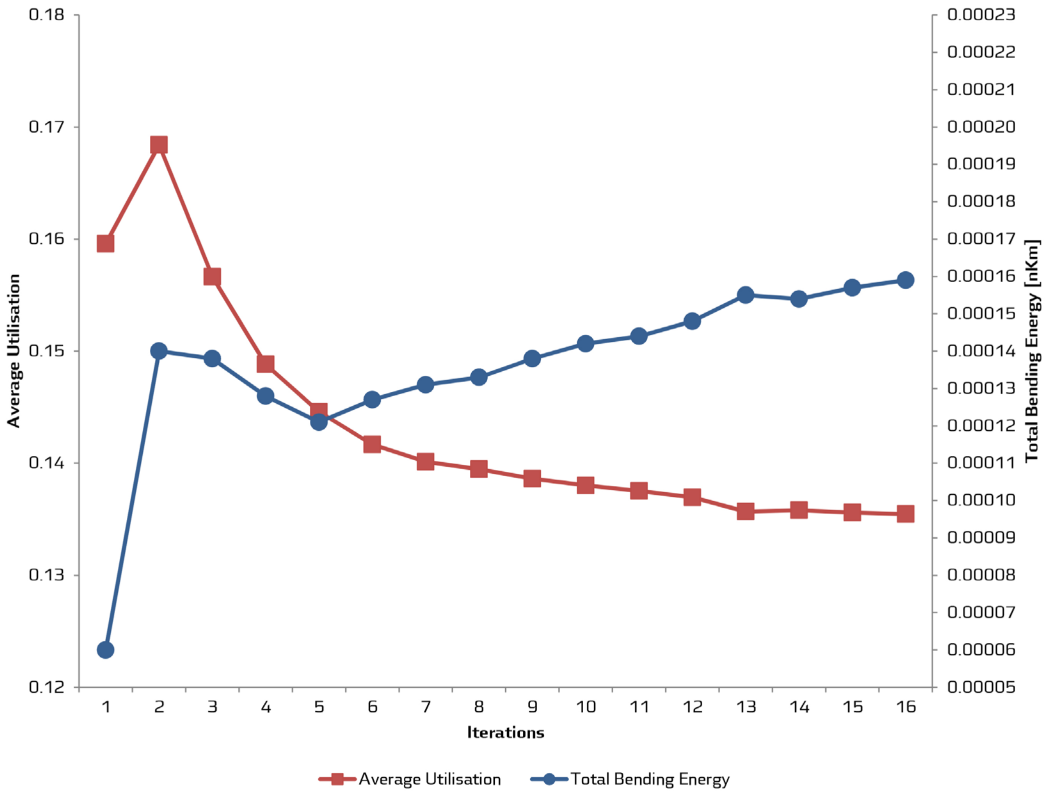


Figure 15: Transformation in utilisation through local deepening of features and resultant strain hardening, exercised iteratively.


0.18
0.17
0.16
0.15
0.14
0.13
0.12
Average Utilisation
0.00023
0.00022
0.00021
0.00020
0.00019
0.00018
0.00017
0.00016
0.00015
0.00014
0.00013
0.00012
0.00011
0.00010
0.00009
0.00008
0.00007
0.00006
0.00005
Total Bending Energy [nKm]
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
Iterations
Average Utilisation
Total Bending Energy

An ABB IRB140 multi-purpose industrial robot is used to fabricate Stressed Skins. During prototyping, panels up to a scale of 150cm x 50cm are produced; the working area for the final panels is approximately 50x100cm. Conventional toolpath generation algorithms generate simple sliced contours in the horizontal plane. However this strategy does not produce optimal results when applied to more complex geometries formed with ISF. To improve control over tooling time and surface quality, we develop a toolpathing algorithm based on the established method of a spiral descent (Jeswiet et al. 2005). This algorithm integrates the grouping of features, the position of features, toolpath length and tooling speed in relation to wall angle (Fig. 18). Additionally, the algorithm is informed by knowledge gained directly through prototyping: this includes the observation of forming limits, optimal working areas, and tooling speed.

Figure 16: (Opposite) Tracking of change in average utilisation for each mesh element, along with total bending energy captured within each panel as depth modulation is introduced and iterated through patterning and forming.

9.7 Discussion

This research demonstrates a mesh-based modelling method that synthesises structural performance interests with locally varying material properties, in the production of an architectural scale installation. The model is based around geometry, properties and mechanics at three scales. With the exception of two "handshakes", the model varies a single mesh topology to manage the complexity of bridging scales and functions while maintaining speed, flexibility and continuity of information flows up and down scales. Further work aims to incorporate the measure of strain into this continuous mesh topology by performing measures on triangular rather than quad faces.

Figure 17: (Opposite) Variable depth patterning on an upper skin panel.

The model inputs include direct user inputs, geometric parameters, material and processing parameters, and feedback from finite element analysis. The micro scale calculations are calibrated through experimental testing of Vickers hardness, and are shown to be an accurate predictor. While at this stage the calculation of local yield strength is limited to informing finite element analyses, a next step will be to understand how parameters at this scale might also activate optimisation processes.

Acknowledgements

This project was undertaken as part of the Sapere Aude Advanced Grant research project "Complex Modelling," supported by The Danish Council for Independent Research (DFF). The authors want to acknowledge the support of several collaborators: Clemens Preisinger and Robert Vierlinger of Bollinger Grohmann consulting engineers assisted in the forming of intuitions regarding

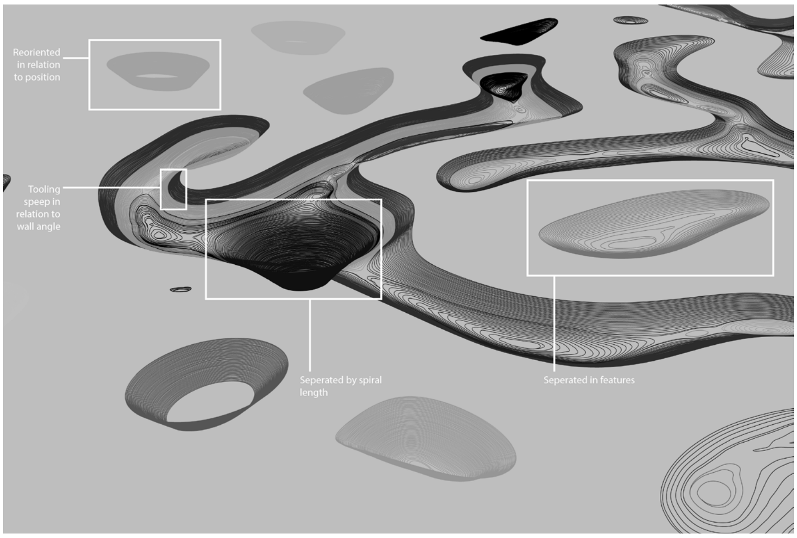


Figure 18: Diagram of key drivers for toolpath extraction and organisation.

structural behaviours and appropriate finite element modelling strategies to represent them; Daniel Piker and Will Pearson provided direct support with both the Kangaroo2 and Plankton libraries, and the development of computational tooling; the research departments DTU Mekanik supplied access to and assistance using their ISF-designated CNC rig, as well as insight into several ISF-related calculation techniques; robotic command and control was enabled through the software HAL; and introductory guidance regarding ISF operations was given from RWTH Aachen.

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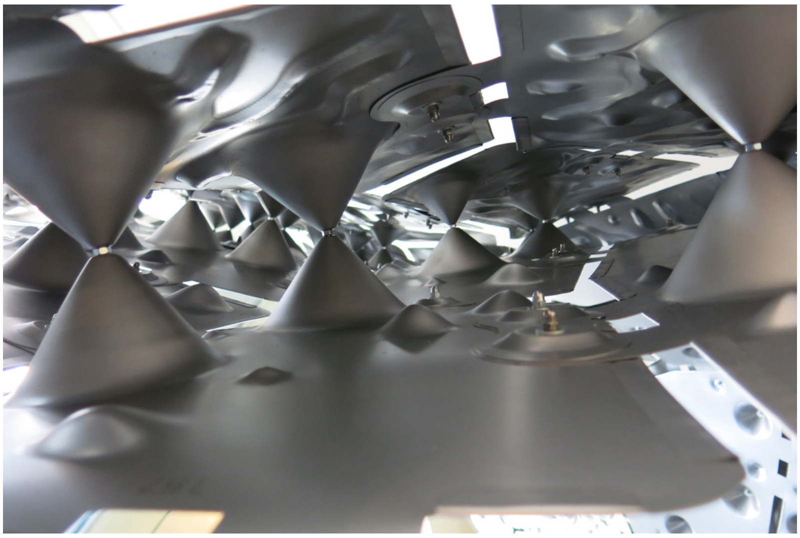

Figure 19: Connectivity between the upper and lower skins

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10. An integrated modelling and toolpathing approach for a frameless stressed skin structure, fabricated using robotic Incremental sheet forming

Reformatted from: Nicholas, P., Stasiuk, D., Nørgaard, E., Hutchinson, C., & Thomsen, M. R. (2016). *An integrated modelling and toolpathing approach for a frameless stressed skin structure, fabricated using robotic incremental sheet forming.* In Proceedings for Robotic Fabrication in Architecture, Art and Desgin 2016 (pp. 62-77). Springer, Cham.

Abstract

For structural assemblies that depend upon robotic incremental sheet forming (ISF) for rigidity, connectivity, customisation and aesthetic, an integrated and accurate modelling process that considers fabrication and forming parameters as well as performance implications at material, element and structural scales becomes critical.

This paper briefly presents ISF as a method of fabrication, and introduces the context of structures where the skin plays an integral role. We then describe the development of an integrated approach for the modelling and fabrication of Stressed Skins, an incrementally formed sheet metal structure. We focus upon the use of prototypes and empirical testing as means to inform digital models about fabrication and material parameters including: material forming limits and thinning; the parameterisation of macro and meso simulations with

calculated and observed micro behaviour; the organisation and extraction of toolpaths; and rig setup logics for fabrication. The validity of these models is evaluated through structural performance, and by evaluating geometric accuracy at multiple scales.

10.1 ISF

Incremental sheet forming (ISF) is a fabrication method that imparts 3D form onto 2D metal sheets. It is driven by 3D CAD models and has been developed for the purpose of industrial prototyping within the automotive industry. In the most typical ISF method, a ball-head tool is moved over the surface of a thin metal sheet, causing a progression of localised plastic deformation (Jeswiet et al 2005). ISF is useful for three reasons. First, it negates the need for time-intensive creation of costly dies (negative forming), instead directly machining semi-finished pieces of metal. Secondly, because forming is highly localized, the force required does not increase with scale, meaning that there is no theoretical limit to formed sheet size (Tisza 2012). Lastly, ISF extends the formability of metals beyond conventional methods, such as stamping or deep drawing (Bagudanch et al 2013). Drivers of new research in this field include the exploration of larger scale applications, typically in the automotive and aerospace industries (Amino et al 2014, U.S. Department of Energy 2013), and improving forming accuracy. The geometry change impacted on the steel sheet is achieved through a local tensile or biaxial stretching of the metal, and is dependent upon a connection between geometric considerations, processing parameters and material properties. As it is stretched the metal undergoes strain hardening or cold working, which increases its strength locally through the accumulation of plastic deformation. This metallurgical transformation attends geometric change, as the sectional thickness of the sheet diminishes relative to stretching. In the context of a lightweight skin, these changes are not insignificant. For example, in Stressed Skins – which uses low carbon mild steel formed at room temperature – sectional thickness reduces in places from 0.5mm to 0.15mm, and strengths increase from 220 to 410 MPa.

10.2 The architectural relevance of ISF

Transferred into architecture, ISF graduates from a prototyping to a production technology that supports mass customisation. Potential architectural applications have been identified, for example in folded plate thin metal sheet structures (Trautz & Herkrath 2009). We identify a further application for ISF in customised, load-adapted architectural designs. Architects use thin metal sheets as cladding panels to provide integrated enclosure, structure and form. Because loads vary over such a building system, performance requirements vary, and customisation of elements becomes a key concern. Using ISF on pre-cut metal cladding panels to add features that locally stiffen the panel, in the locations and to the extents needed, would mean significant efficiencies of material use and reductions for supporting structural systems.

10.3 ISF for stressed-skin structures

In this research, the ISF process is used to fabricate an architectural stressed skin structure. Such systems are typically a hybrid assembly in which a thin skin is structurally active, bearing both planar and shear forces and providing significant rigidity by continuously wrapping an underlying, compressive frame. They are an intermediate between monocoque and rigid frame assemblies, and have been particularly associated with the early application of metals in lightweight structures. In their design, rigidity is a central concern at multiple scales: rigidity against instability in the whole structure, against local buckling of the components that carry compressive load, and against micro buckling or 'wrinkling'.

Stressed Skins develops a structural approach in which the skin carries planar and shear forces, but without the use of an additional framing system, at the scale of a pavilion. Research at RWTH Aachen has established ISF as structurally feasible at this scale (Bailly et al 2014), in the case of formed panels spanning between a hexagonal continuous framing structure. Recent research explores doubly curved sheet metal panels for free-form metal skins (Kalo & Newsum 2014) and self-supporting structures (Bailly et al 2015) which utilise cone geometries as means to reach from one skin to another. These have been developed to prototype scale.

Stressed Skins (fig.1) presents as an asymmetric tunnel, which cantilevers at

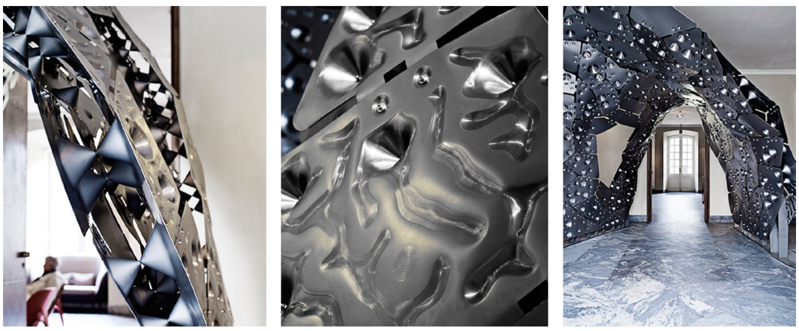


Figure 1: The research structure *Stressed Skins*: structure and details

one end. The structure consists of 186 unique planar, pentagonal panels. These are arranged into an inner and outer skin. The framing system for typical stressed skin assemblies is replaced by the introduction of geometric features for resisting local buckling and structural connections, both continuous within each skin and for managing shear across inner and outer skins. These are produced through the custom robotic ISF of individual panels.

10.4 Prototype, modelling & fabrication: an integrated approach

Stressed Skins is developed through multiple iterations of physical prototypes and computational models. In general, observations from physical prototypes feed forward into the digital environment. The digital environment addresses the multiscale nature of the forming process and the structural assembly. In this approach, different computational models, specific to particular scales of parameterisation, behaviour and decision making, are made critically interdependent upon one another.

Computational considerations

The digital modelling of Stressed Skins is informed by parameters and limits derived directly from these physical prototypes. Three modelling scales – macro, meso and micro – are considered to be markers along a structural continuum (fig. 2). In general, the macro scale refers to overall geometric configurations and predictions of its structural performance. The meso scale considers the level of the panel and its detailing, and implements geometric transformations related to connectivity, stiffening, and component-level tectonic expression. Finally, the micro scale relates to the calculation of material implications at the

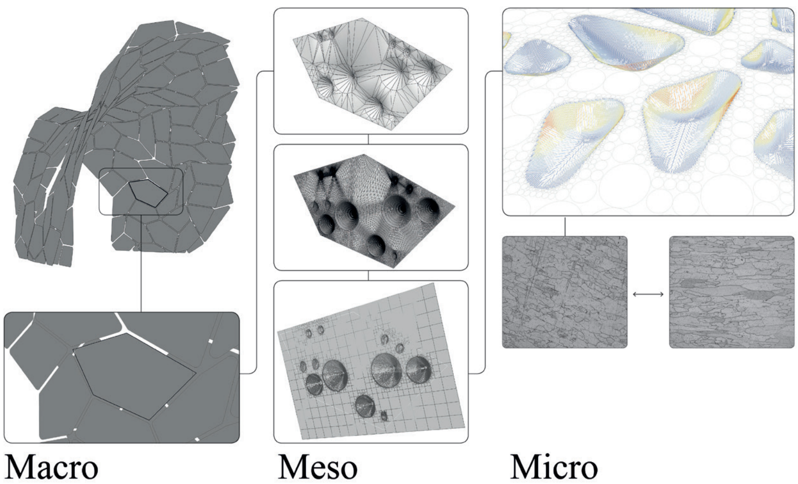


Figure 2: Interscalar relations: macro (left), meso (center) and micro (right)

most discretised level, which includes the thinning and hardening of the steel sheet that results from forming. The modelling does not include the actual simulation of the ISF fabrication process, but only the expected material transformations introduced through it.

The multi-scale modelling approach is comprised of techniques which enable the information generated at each scale to flow both up and down the continuum. Here, an adaptive mesh refinement method is used to support localised variations in resolution and information flow. From the perspective of the design development, these include: overall form-finding and panelisation operations; global structural analysis and adaptive specification of connectivity arrays; and recursive local tectonic pattern formation which depends upon finite element analyses and is further informed through the calculation of forming strains and material thinning. The features of a half edge mesh – its vertices, half-edges and faces – are coupled with a series of lists, dictionaries and Grasshopper data trees that effectively bundle within mesh elements critical design data related to: topology, form-finding and geometry; structural behaviour; material characteristics; connection detailing; and patterning and tectonic expression (Nicholas et al. 2015).

Physical considerations

Physical prototypes have played a key role in determining the parameters and limits of mass customisation. Parameters that informed the digital modelling include individual panel constraints related to size, orientation, and formable territory; the development of connection and assembly strategies; change in material properties; and forming limits in regards to both feature geometry and tooling time. Samples were prepared to systematically vary multiple processing parameters: tool type (either hammer or point), tool movement speed, feature angle, and to measure strain hardening and thinning. To integrate factors inherent to the fabrication setup, all samples are produced using the same rig used for final production.

ISF setup

An ABB IRB 140 six-axis multipurpose industrial robot is used to fabricate Stressed Skins. The wall-mounted robot arm is situated above a flat table which bears a clamped, re-orientable MDF jig (fig. 3). MDF dies are fixed to this jig and where necessary are supported from below using a collection of standard elements. The dies are laser-cut templates that define the outlines of desired formed geometries, where those geometries cut the plane, and provide

Figure 3: (Left) ISF setup

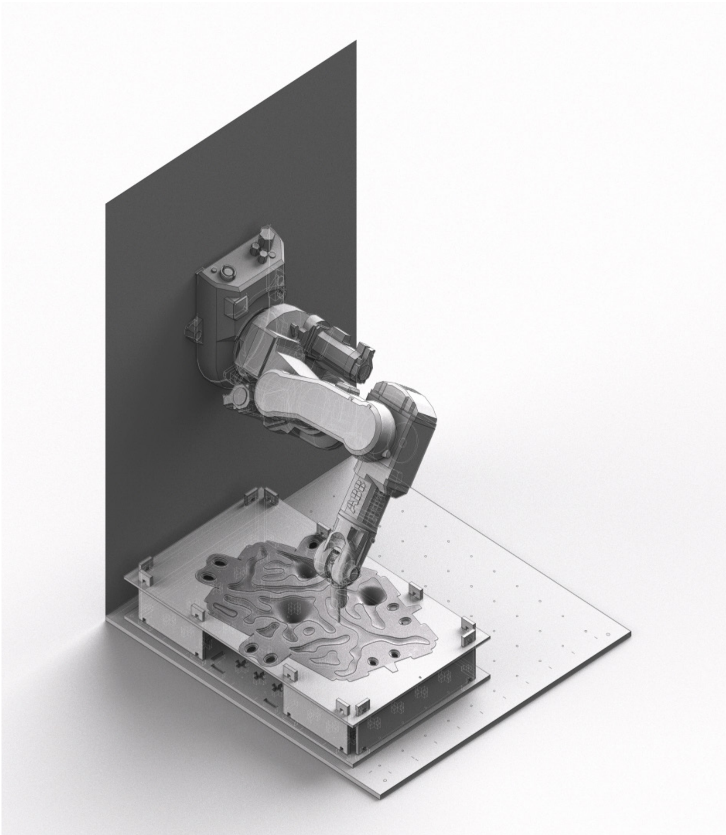
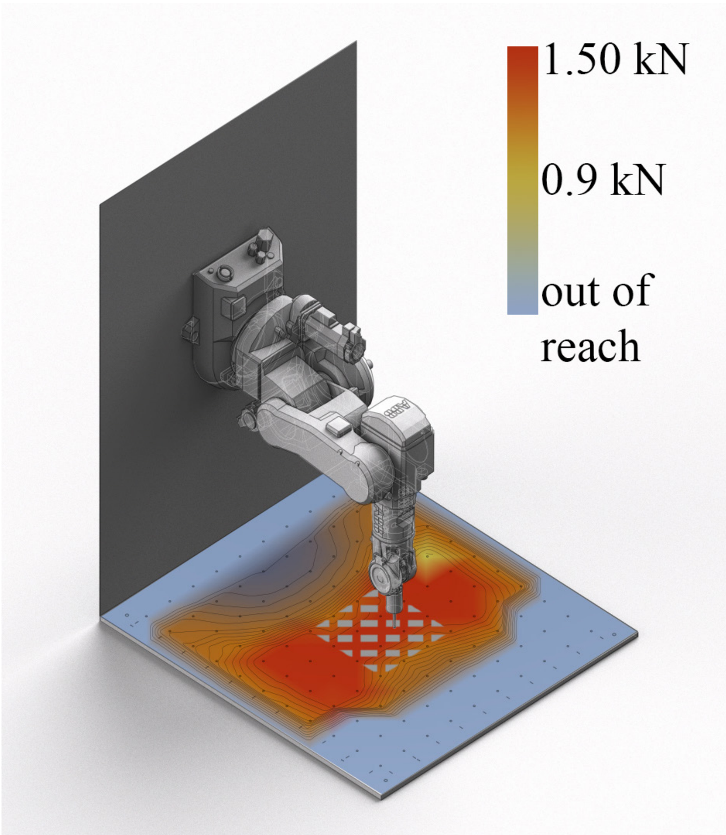


Figure 4: (Right) Force capacity of robot (colourised) and area prone to singularity (shown in grid)



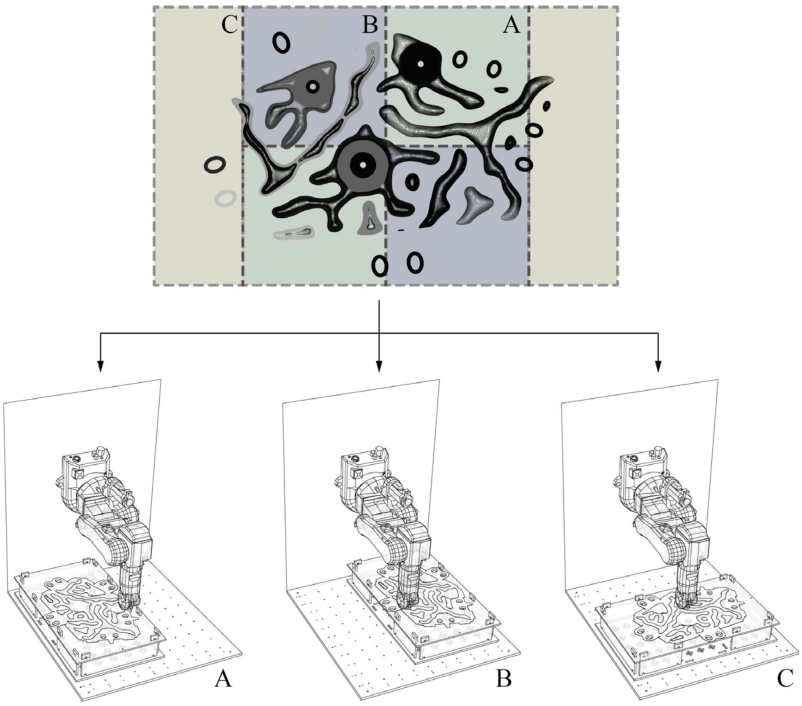


Figure 5: Reorientation logic and jig positions

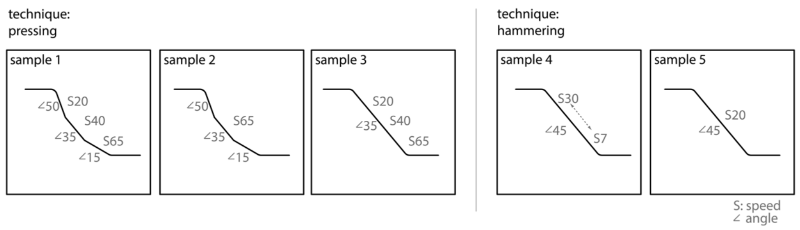


Figure 6: Systemic testing of angle and speed parameters

resistance for the steel sheets in areas intended to remain planar. Steel sheet blanks are fixed to the dies along their edges with bolted MDF blocks.

Position of features

Through empirical testing, the capacity of the ABB irb 140 to exert a downward force was established for the working area (fig. 4). Because of this varying strength capacity, the position of features proved to have an impact on the forming accuracy, and in some cases resulted in the robot's failure to apply sufficient force to form the steel. To counter this problem, which is to a large extent linked to the size and specification of our robot system, 6 different forming positions were defined. An analysis of target locations per feature enabled toolpath distribution across these forming locations (fig. 5). As a result, forming was concentrated in areas of maximum strength.

Production of samples for testing

Samples were prepared using two alternative forming methods. The first of these was a pneumatic hammering tool, where force was generated via the

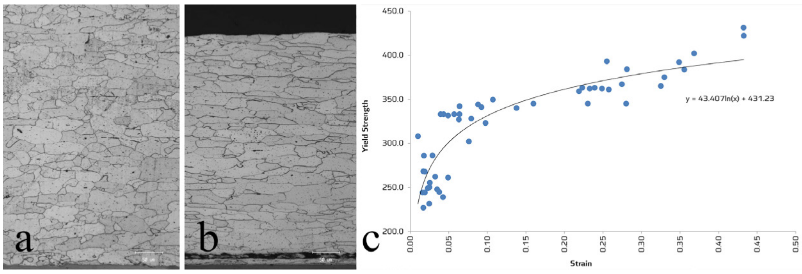


Figure 7: a) Initial grain size, b) grain deformation induced by forming, c) relationship between local strains and measured yield strength calculated from Vickers hardness measurements.

stroke of the tool tip. The second method, a single-point pressing approach that utilises the robot's capacity to impart force, was understood and developed based on access to an ISF-designated CNC setup at DTU Mekanik.

Several processing parameters were varied in a systematic fashion across five samples – the forming method, the tool speed and the wall angle. Both forming methods were tested in order to understand their relation to strain rate. The relation between tool speed and wall angle was tested to understand how these parameters affected formability. The speeds varied between 20 – 65mm per second, and the wall angle was tested at 15, 35 and 50 degrees.

Testing of samples

Within the range of speeds and angles tested, all samples were successfully formed. Visual monitoring of the grains and measurement of thickness at the same points was achieved using optical microscopy (fig. 7) at 5 points on the cross-sectional thickness of each sample. Their local increase in strength was monitored using Vickers Hardness tests with a 5kg load measured at 50 points on the cross-sectional thickness of the sample. The resulting hardnesses were converted to estimated flow stresses and correlated with the local strains. Flow stress is the yield strength of the metal as a function of strain, and describes the point at which the material enters plastic deformation. The conversion between hardness and flow stress is stress (MPa) ≈ 3·VHN, where VHN is the Vickers hardness number (Tabor 1951). Yield strength equates to flow stress.

Results

The hammering technique imparts plastic deformation through the rapid sequential impacting of a tool against the surface. This involves a much higher speed of tool motion and therefore produces larger strain rates and leads to a greater straining of the sheet but not, in the samples tested, to higher flow stresses. In this respect, hammering does not offer obvious advantages compared to the pressing technique. Further, our observation was hammering was associated with greater springback, and that we were able to better achieve the target form through the pressing technique. Based on these observations as well as results from the results of the Vickers hardness tests, the pressing mode of forming was identified as the fabrication method of interest.

It was found that in the range of 30 – 60 mm per second the tooling speed had a large impact in both the surface quality and formability of the steel sheets and that the amount of impact had a direct connection to the wall angle. However there was no observed impact on the material properties and that at this range, the impact of tool speed is negligible to resultant strain hardening.

Eq. 1 is then derived from the measured relationship between local strains induced by forming and the measured flow stress by fitting the logarithmic curve to the observed data points (fig. 7c)

$$(1) \quad \sigma y = 43{,}407 \ln(\epsilon) + 431{,}23$$

Measured thickness correlates with results based on the calculation of thickness strain ($\epsilon 3$) and can be calculated due to the rule of volume constancy:

$$(2) \quad \epsilon 1 + \epsilon 2 + \epsilon 3 = 0$$

10.5 Synthesis of computational and physical considerations the example of a panel

The digital model and processes of physical prototyping are synthesised in the development of geometric features within a panel, toolpath extraction and organisation methods.

10.5.1 Panel and connection arrays and global FE simulation

The panel arrays for both layers of Stressed Skins were developed through a stepwise accumulation of panels onto two respective target surfaces according to a pentagonal planar tiling strategy. The targets were derived as being variably offset from a baseline surface that was developed both to accommodate occupancy requirements on the site and to generate suitably challenging structural performance demands through its spanning and cantilevering. The variable offset was calculated based on an initial shell FEA, with greater offsets – and structural depths – assigned to areas of high utilisation. A constraint-based dynamic form finding system – a beta scripting library of the

Grasshopper plug-in Kangaroo2 – was used to adapt and planarise each panel as it adhered to its respective offset target design surface. Following this initial panel organisation, a series of connection cones were solved between the two skins. These cones form the primary basis for managing the structural shear requirements, taking on much of the role played by the compressive frame in traditional stressed skin structures. Here they were located to maximise diverse connectivity across multiple panels between the upper and lower skins, and oriented in response to a second FEA that identified shear force vector lengths and directions. A third FEA was performed following this precise locating of the connection cones, and translation and rotation nodal displacements were extracted from the model at all connection points between panels, both within and across skins.

10.5.2 Informed patterning and local FE simulation

The prior understanding of the relationship between geometric forming and the consequential material hardening was then integrated with these connection point translation and rotation vectors into an iterative feedback design and analysis cycle for the purpose of locally introducing performance improvements into individual panels specifically to resist in-panel bending forces. This was achieved through the variable-depth forming of a pattern onto each panel, integrated with the base inter-skin connection cones that provide primary structural depth and accommodate the transfer of shear forces within the assembly.

The pattern was first generated as a flat, graphic element over all panels on the mesh. An implementation of the Gray-Scott reaction-diffusion algorithm on the design mesh was used to achieve this. Beyond its aesthetic, this algorithm was selected for a two key reasons: its generally isotropic nature enabled

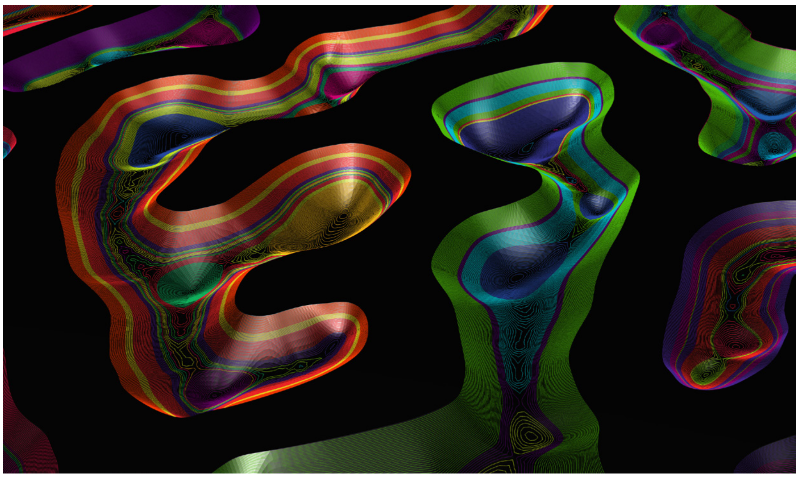


Figure 8: Grouping of features

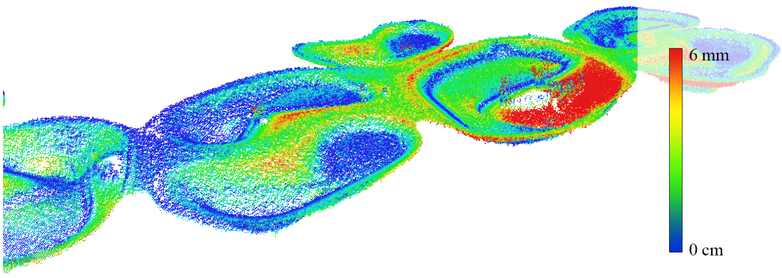


Figure 9: Range of deviation between predictive model and formed panel

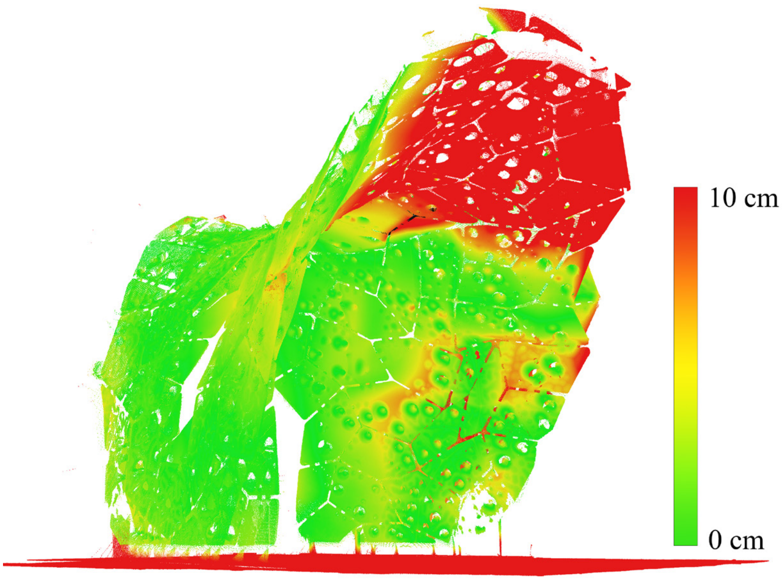
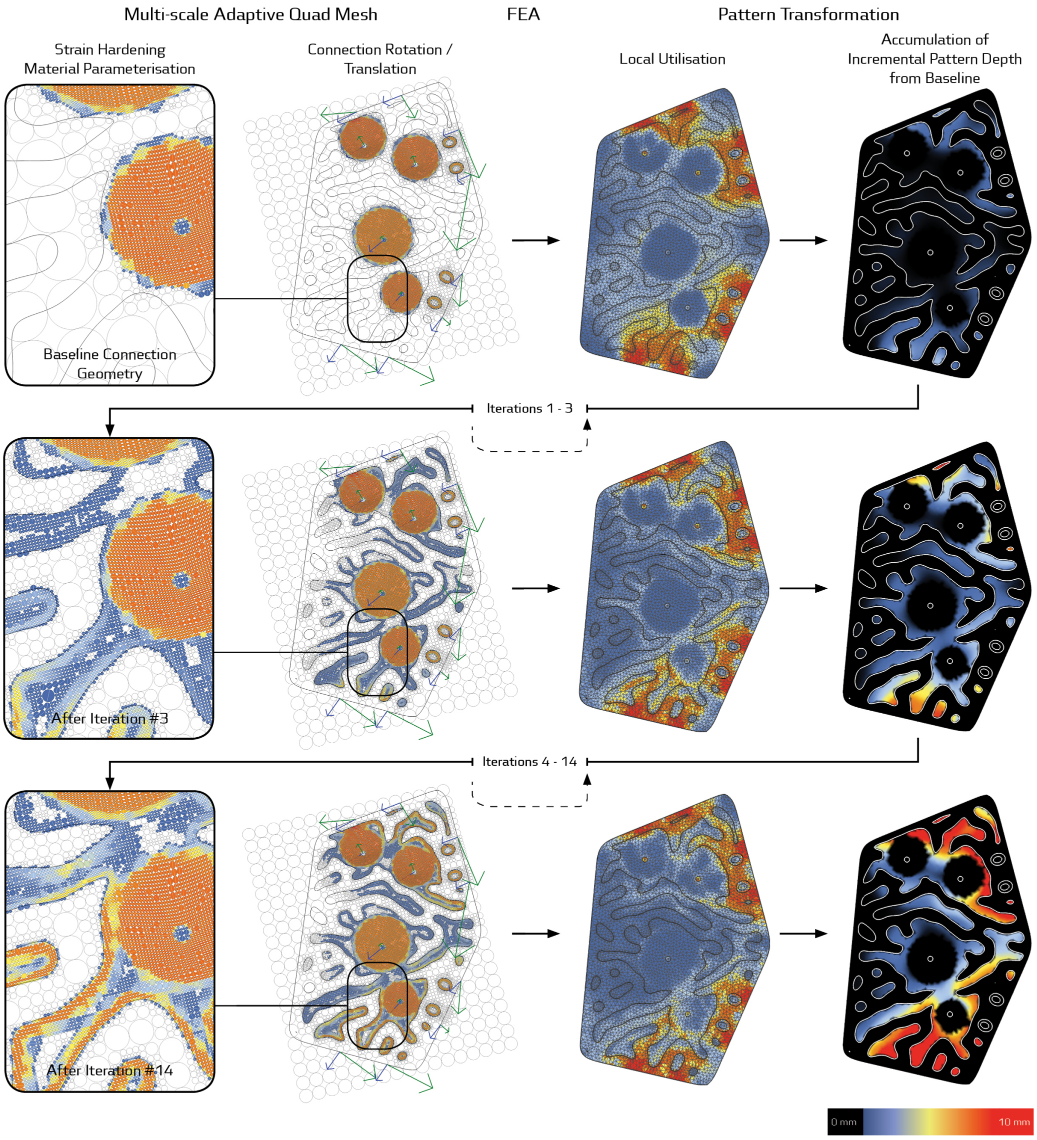
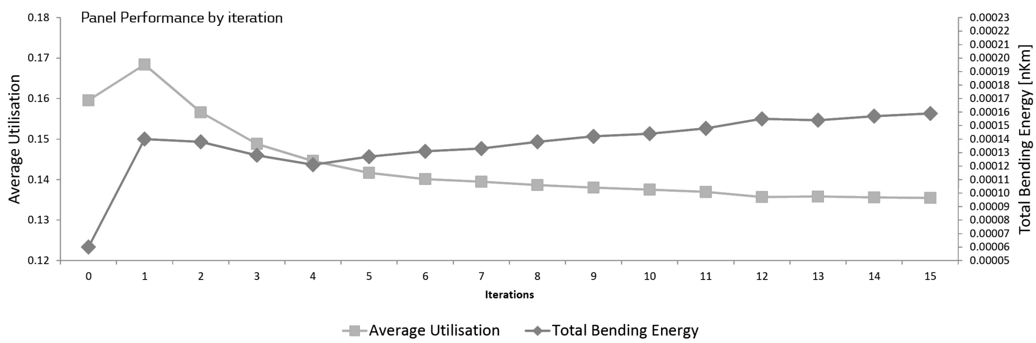


Figure 10: (Left) Range of deviation between predictive model and formed build assembly


Multi-scale Adaptive Quad Mesh
FEA
Pattern Transformation
Strain Hardening
Material Parameterisation
Connection Rotation /
Translation
Local Utilisation
Accumulation of
Incremental Pattern Depth
from Baseline
Baseline Connection
Geometry
Iterations 1 - 3
After Iteration #3
Iterations 4 - 14
After Iteration #14
0 mm
10 mm


Panel Performance by iteration
Average Utilisation
Total Bending Energy [nKm]
0.18
0.17
0.16
0.15
0.14
0.13
0.12
0.00023
0.00022
0.00021
0.00020
0.00019
0.00018
0.00017
0.00016
0.00015
0.00014
0.00013
0.00012
0.00011
0.00010
0.00009
0.00008
0.00007
0.00006
0.00005
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
Iterations
Average Utilisation
Total Bending Energy

resistance to bending in multiple directions, and its form could reliably be cut into the MDF dies used during forming. This baseline pattern worked as a scaffold to receive additional depth. This additional depth was realised through an iterative process that is diagrammed in the second full page image and described here. First, each panel begins as flat in all areas except for the features used for both inter and intra skin panel connections. Over each panel submesh, an adaptive quad mesh is arrayed and inscribed ellipses used to determine the local strain introduced in the forming of these baseline features. Eq. 1 is deployed to locally differentiate yield-strength material settings for each face in the primary mesh, and an FEA is executed for the individual panel, using the translation (blue) and rotation (green) force vectors derived from the global FEA. Resulting utilisations are extracted. Here, note that areas within each panel that have been hardened due to forming (as in the deep connection cones) tend to have significantly higher strengths, and therefore lower utilisations. High utilisation areas then drive the local introduction of incremental depth, which is here visualised as incremental changes from baseline features, with black being zero change. This process of transforming material settings, applying connection nodal translations, and adding local pattern depth is then iterated up to fifteen times per panel, resulting in a steady decrease in utilisations for each panel due to strain hardening, and greater bending energy due to geometric stiffening resulting from added depth where it is useful. Finally, each panel is subdivided to a finer level of resolution, and initial contours are extracted for toolpath generation.

Figure 11: Integration of strain hardeing calculation with parameterisation of FEA model and specified response through increase in depth of patterning

10.5.3 Fabrication and toolpath generation

An algorithm was developed to derive tool paths from the model geometry, based on contours cut from a design mesh. The progression of the algorithm was 1. Grouping of features, 2. Position of features, 3. Tooling speed in relation to wall angle. This order was developed to firstly calculate the entire toolpath, then divide it into modules, and lastly to add information about speed to the target positions. To improve control over tooling time and surface quality, the toolpathing algorithm is developed based on the creation of spirals, an established approach for ISF (Filice et al 2002, Bramley et al 2005).

Grouping of features

With the basis being horizontal contours, a strategy for grouping the section curves was developed. By checking the section curves for inclusion in the domains of the previous layer, groups of curves was created in order to make multiple continuous spiraling toolpaths that allowed forming of complex geometry, but ensured no metal was being formed unconsciously or tried forming twice. Fig. 8 shows an example of a colour coded grouping, revealing the complexity in both geometry and toolpath.

Position of features

To ensure features being formed in optimal position in relation to the strength of the robot, each spiraling toolpath was divided into 1000 points. Each point was checked for inclusion in predefined areas (fig. 5). The toolpath was then transformed into the area that recorded the highest percentage of inclusion.

Tooling speed in relation to wall angle

The production schedule for Stressed Skins required working at the maximum permissible speed, with consideration to formability and surface quality. Building on the knowledge obtained from the tested samples, further exploration showed that if the wall angle did not exceed 45 degrees a speed of 65 mm/s could be used, but as wall angle got higher the speed needed to be lower to ensure both surface quality and formability. With our setup we reached a limit of a 60 degree wall angle which could be achieved with a tool speed of 30 mm/s. Based on this testing, a linear relation between angle and tool speed was used to set a unique tool speed for each target point along a toolpath:

$$(3)\quad S[mm/s] = -2.333*A[deg]$$

10.6 Assembly and evaluation

Fabrication of the 187 panels took a period of 10 weeks, and the assembled structure was exhibited at the Danish Design Museum in April 2015. Because the structure is characterised by a high degree of connectivity successful assembly relied upon accurate forming and low tolerances. Geometric accuracy has been a key concern regarding ISF since its inception, with typical geometric tolerances of more than ±3mm within a part (Allwood et al 2005). From the perspective of traditional architectural distinctions regarding structural hierarchy these tolerances are feasible, however in the case of a stressed skin structure they need to be tightly managed and not allowed to build up over the entire structure.

A Faro Focus 3D 120 scanner was used as a means to measure geometric accuracy and structural performance. At the scale of panel, forming accuracies were measured to have a 2 mm standard deviation (fig. 9). This was accounted for via the inclusion of a 4 mm spacer at connection points between inner and outer skin.

One month after installation, the assembled structure was scanned. The maximum deviation to the geometry predicted using the finite element model was 10cm, recorded at the extremity of the cantilever (fig.10).

10.6.1 Results and Conclusion

This research reports the modelling and fabrication of an incrementally formed, stressed skin architectural structure. A robotic ISF process is used to form rigidising geometries within thin steel panels, as well as all connections between those panels. ISF possesses great architectural potential in the area of mass customisation, however this application requires a tight coupling between fabrication process, material properties and the digital design model. To date, research has been focused on the production of single elements and small collections, as opposed to highly integrated structural assemblies. This paper extends the scope of architectural applications by developing a highly integrated structural assembly and an associated digital modelling method.

We introduce and evaluate a modelling method that is informed by fabrication parameters and material properties, which are established through prototyping and empirical testing. The model incorporates the specifics of a fabrication environment as well as empirically derived material hardening and thinning data. This information is used to parameterise macro and meso finite element simulations with calculated micro behaviour; to define and extract toolpath information; and to inform rig setup logics for fabrication.

The high level of integration between modelling and prototyping enabled the simulation to incorporate a level of information not typical within architectural modelling, and a fabrication process where the relationship between tool speed and wall angle was optimised. The successful assembly of the panels, some supporting up to ten unique connections, demonstrates that incrementally formed frameless structural assemblies are possible at this scale.

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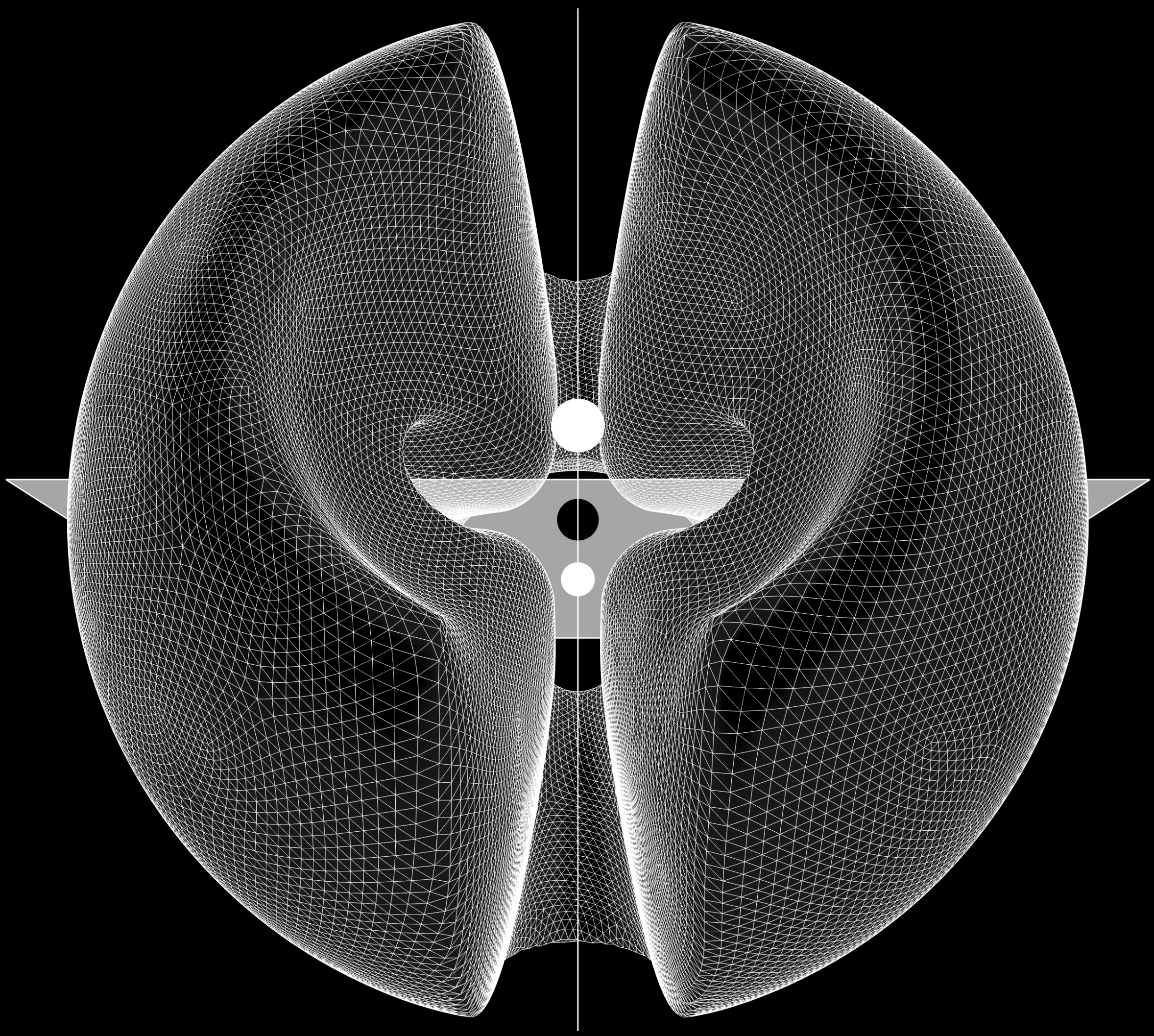
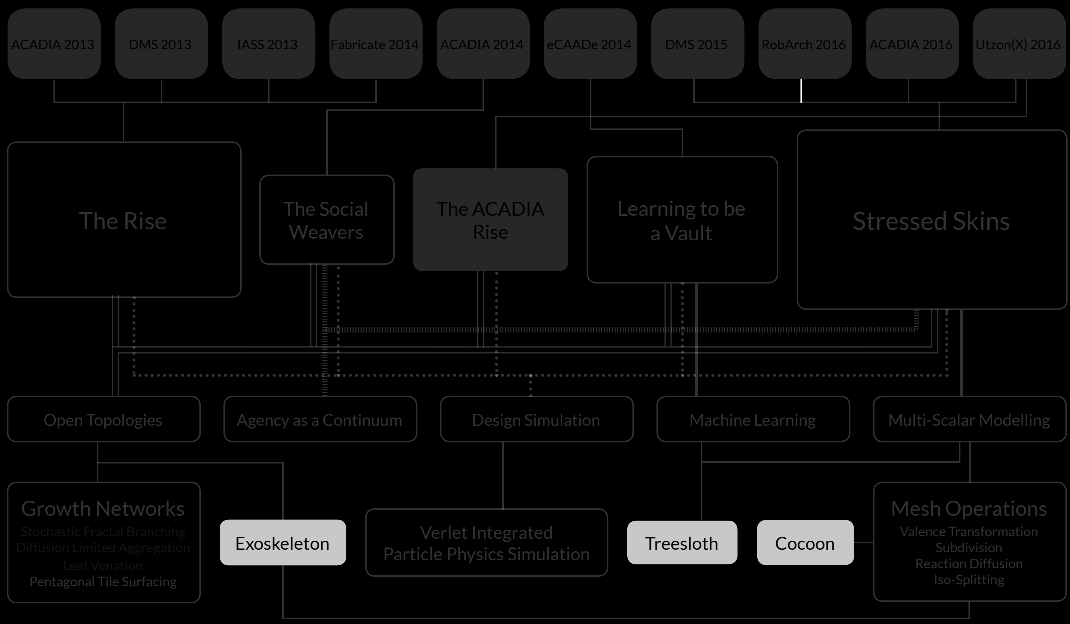




Publications VI: Digital Instrumentation

Instrumental probes

This research project has been realised within a digital-material practice, where research through design supports knowledge production via a catalytic relationship between design and discursive reflection. The larger experimental projects that define the principal body of this research are themselves partly comprised of collections of supporting experiments, which typically work either as design probes, as instruments, or as some combination of the two. Design probes are used to explore or investigate some topic of interest or concern relevant to the broader experiment or research practice, and instruments may be either directly used within the experiment or instead simply become standalone tools for more generalised usage. As a result of pursuing this methodology, in addition to the output and findings of the larger experimental projects, the overall research project has also produced a series of general computational tools, instruments, and digital implementations of various algorithms.

Several of these instruments have been disseminated to the design community in the form of either plug-ins or definitions for the Grasshopper visual scripting environment within the 3D modelling software platform Rhino. The three primary plug-ins that have been developed as part of this research project and made freely available to the Grasshopper user community – named *Treesloth*, *Exoskeleton*, and *Cocoon* – have in total been downloaded more than 35,000 times. In addition to these plug-ins, which deliver custom "components" for use in the Grasshopper visual scripting environment, a variety of standalone files – or definitions – that implement or other algorithms have also been distributed as a direct product of this research project. This chapter specifically discusses the implementation of Diffusion-Limited Aggregation and Mesh Subdivision in this last context, relative to their respective roles as design probe and direct instrument, although over the course of this PhD project several additional definitions and tools for design exploration have been shared with the community, such as for discretising intersecting curve networks into collections of closed regions (Stasiuk 2013a) and the production of stochastic fractal branch networks (Stasiuk 2013c).

These digital instruments supply a small but important component of this PhD's contribution, supporting the research diary of the larger experimental projects from which they emerged while also providing useful or interesting tools to the academic and professional design practices that engage with computation. This chapter describes these contributions.

Treesloth

The fact that CAD modelling platforms enable users to capture and dynamically visualise geometric information about spatial artefacts may sometimes obscure their fundamental nature as data storage and management platforms. For design projects that must handle or resolve a great number of elements, the efficient and efficacious negotiation of these as data collections emerges as a primary challenge for designers. This is especially true for computational design platforms and within complex projects that aim to build up robust feedback loops and interdependencies between partial models and which algorithmically assign or categorise individual elements. Here, distributed assemblies that reflect nested relational hierarchies and dynamic parameterisation techniques produce significant overhead in terms of model setup and maintenance, especially when the design aims to ensure flexibility, stability and robustness.

Grasshopper – the visual scripting environment that interfaces with the CAD modelling platform Rhino – relies on a custom data structure for negotiating and managing nested collections which it calls the data tree. A data tree is similar to a dictionary, which in computer programming is a commonly-used data structure for digitally storing information that can be quickly retrieved. Dictionaries rely on key-value pairs, where each key is a unique identifier for an entry, and each value is an object of any type specified by the programmer. What distinguishes data trees is that the value of the pair is an object collection (or list of objects), and the key of the pair is a mutable object called a data path.

Data paths in Grasshopper are dynamic arrays of integers. They are represented by a single string of semi-colon separated integers wrapped in curly brackets (e.g {0}, or {0;1} or {0;1;1;5}). As operations that introduce (or reduce) hierarchical complexity are performed within Grasshopper, data paths store relevant operational changes to ensure that collections may be better understood as lists of lists by dynamically adding new values to these arrays. For example, when operating on multiple curves in a single list, a user executes a division command, where each curve should be split into a collection of points, it is frequently essential that those points be captured and organised in such a way that the user can access each different collection discretely. For many users of Grasshopper, the effective management of data trees is a primary hurdle to achieving fluency or expertise.

Treesloth was developed as a plug-in to enhance the user experience in working with data trees in Grasshopper. It emerged to enhance my own workflow in managing complex data collections, specifically to collapse unwieldy Grasshopper files with many elements into single components, for ease of application, robustness of operation, and speed of process. *Treesloth* contains several components, whose role variously 1) improves key-matching and filtering when combining adjacent lists, 2) enables expanded splitting, sorting, renumbering and stacking operations, and 3) allows for the integration of collections at varying hierarchical stages in the execution of complex transformations, and 4) enables efficient external storage and retrieval operations that support data sharing without losing critical structural metadata. *Treesloth* was used extensively throughout this research project, beginning with its application within *The Rise*, and its development has been ongoing, with a focus on continuous improvement throughout, with features added to support new processes and operations.

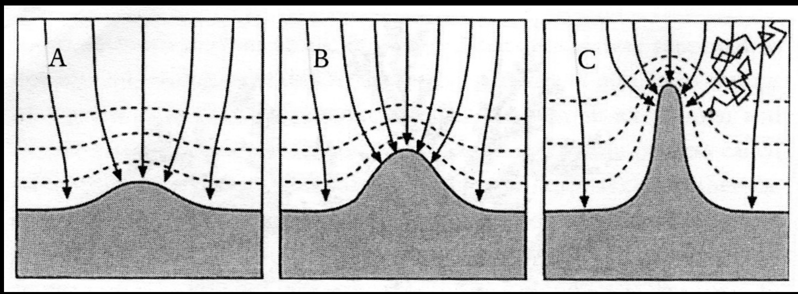


Figure 1: How the basic growth algorithm for DLA favors the incremental likelihood that existing elements will undergo a self-reinforcing grow cycle. Image: (Ball 2009)

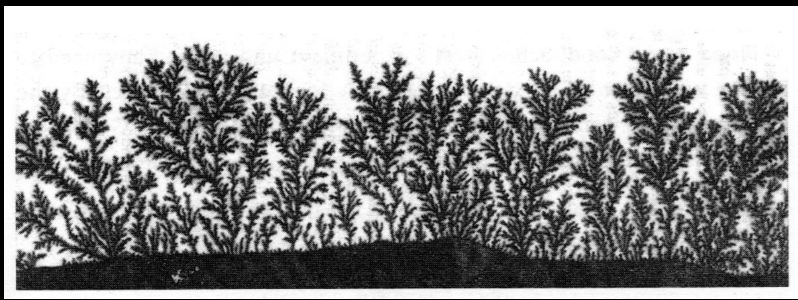


Figure 2: The type of natural electro-deposition process that informed the development of the DLA algorithm. Image: (Ball 2009)

Diffusion-Limited Aggregation

Diffusion-Limited Aggregation (DLA) is a method for describing a form of growth that is exhibited in both living and inorganic systems (Witten and Sander 1981). It is commonly used to model growth systems that are activated through mineral accretion, such as in copper sulphate solutions activated through electrodeposition, but it has also been extended to describe such varied phenomena as the growth of certain types of coral or the formation of frost. It has also has been used to effectively describe the formational processes of unplanned urban centres (Fotheringham, Batty, and Longley 1989).

A basic diagram for modelling the action of DLA growth systems relies on the use of the "random-walk" function that describes Brownian motion, which originally termed in 1828 by the botanist Robert Brown to describe the seemingly random movement of pollen through air. In DLA, individual particle-agents are activated sequentially within a bounded Euclidian space that contains some baseline geometry. In simplest form, these particle-agents are located within this initial boundary and over a series of time-steps instructed to "walk" in an ongoing series of random directional vectors. This action can be partly directed by designer by favouring a specified vector, but in its most basic form agents are simply allowed to "walk" blindly within the boundary space. As each particle moves in step-wise fashion, it is

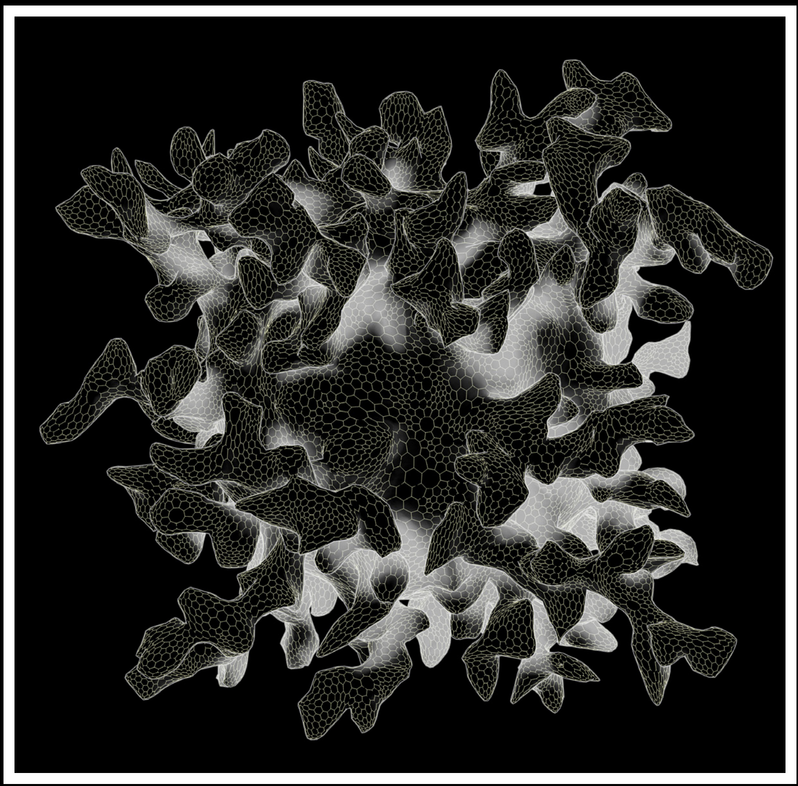


Figure 3: Mesh grown from a spherical base condition using the implementation of the DLA algorithm presented here.

tested at each step for its proximity to the baseline geometry. If it falls within a set threshold, the particle is determined to have accreted, and the baseline geometry grows in a vector reflective of the agent's last velocity. If a particle walks out of the boundary space without striking the baseline geometry, it expires and a new agent is introduced into the simulation. The branching geometries that are formed through DLA become self-reinforcing in that the space expanded during a particular branch's growth due an individual particle enlarges its total surface area relative to the entire baseline geometry, and in turn makes it increasingly likely to be struck again. As a result, certain branches randomly self-select to grow at greater rates than others.

The design probe presented here is a programmatic implementation of DLA written in Grasshopper, and made available to the user community (Stasiuk 2013b). It is initialized from a condition where a simple triangulated mesh surface proves a growth substrate, and which is placed within the bounding box for particle containment. Through a stepwise activated simulation, a series of particles are released one at a time into this boundary condition and moved with Brownian motion. At each step, the current particle is tested relative

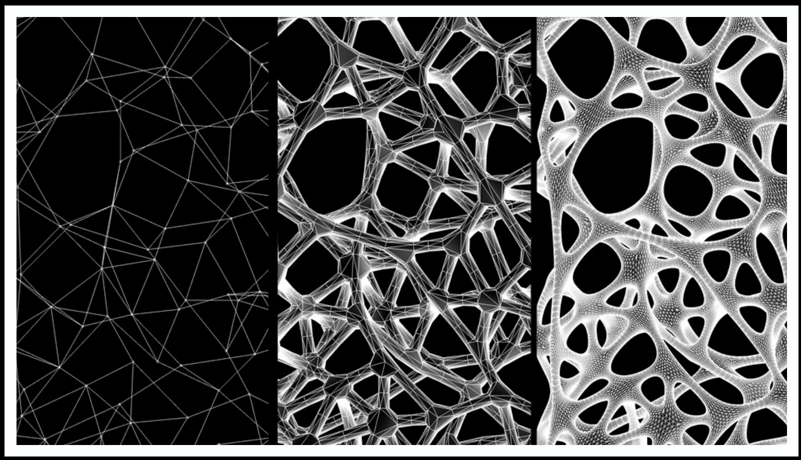


Figure 4: The Exoskeleton algorithm transforming a line network into a thickened wireframe representation.

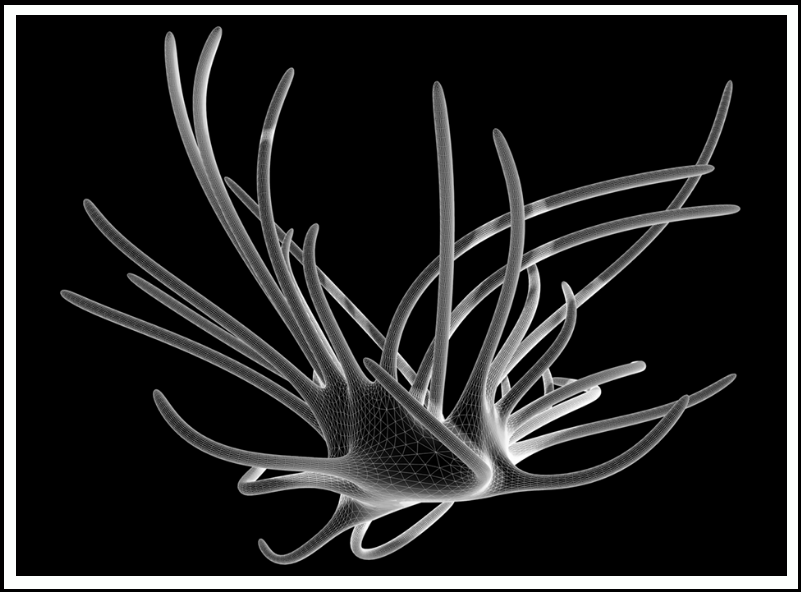


Figure 5: An experimental implementation of Exoskeleton converting a collection of curves into a watertight mesh.

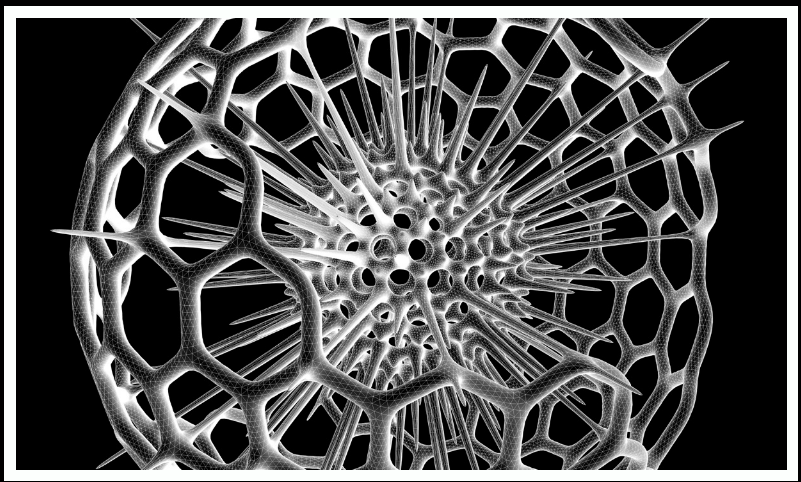


Figure 6: A radiolarian modelled with Exoskeleton

to the mesh. If it falls within a specified distance threshold, it registers the mesh face to which it has struck. This face is then extruded along the vector of the face to the particle that has struck it, after which the next particle is introduced into the system. The simulation is either run for a set number of iterations or until the user terminates its operation.

This modelling system was employed as an early design probe for the project *The Rise*, specifically investigating the potential for growth algorithms to activate open topologies. Here, the model is endowed with a specifically non-deterministic capacity for morphogenesis, adding incremental data structure to the mesh itself and requiring an active process of re-parameterisation. Although the application of DLA was quickly determined to be inappropriate for the architectural questions at hand – there was little implication of either material system or capacity for a directed or goal-oriented process of growth – the exploration operated as a proof of concept for the notion that dynamic, accreting and non-deterministic parameters could be rapidly realised and deployed.

Exoskeleton

Exoskeleton is a Grasshopper plug-in that was created in collaboration with Daniel Piker (Stasiuk and Piker 2014). *Exoskeleton* converts networks of connected lines into thickened, wireframe meshes. The algorithm it relies on is described in detail by Vinod Srinivasan, Esan Mandal and Ergun Akleman (Srinivasan, Mandal, and Akleman 2005). The algorithm starts from a user-supplied list of lines whose endpoints intersect with one another in a three dimensional graph of nodes and struts. The user the number of vertices for the sectional profile of each strut, and also supplies lists of values corresponding to each strut for its width at the start and end, respectively. The

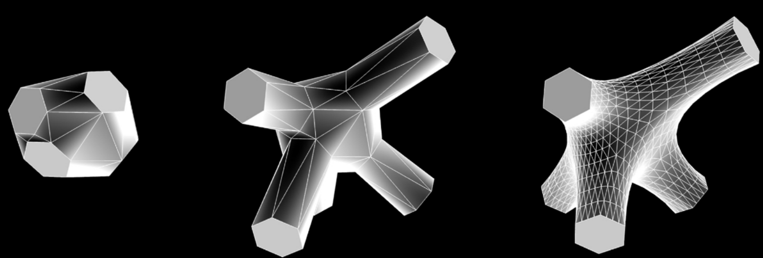


Figure 7: Convex hull approach to node development for Exoskeleton plug-in, where polygonal strut cross sections define initial vertices for convex hull solving.

Figures 8 & 9: (Opposite) Digital artefacts developed using the *Cocoon* plug-in for Grasshopper. These demonstrate the use of negative charges for geometric subtraction.

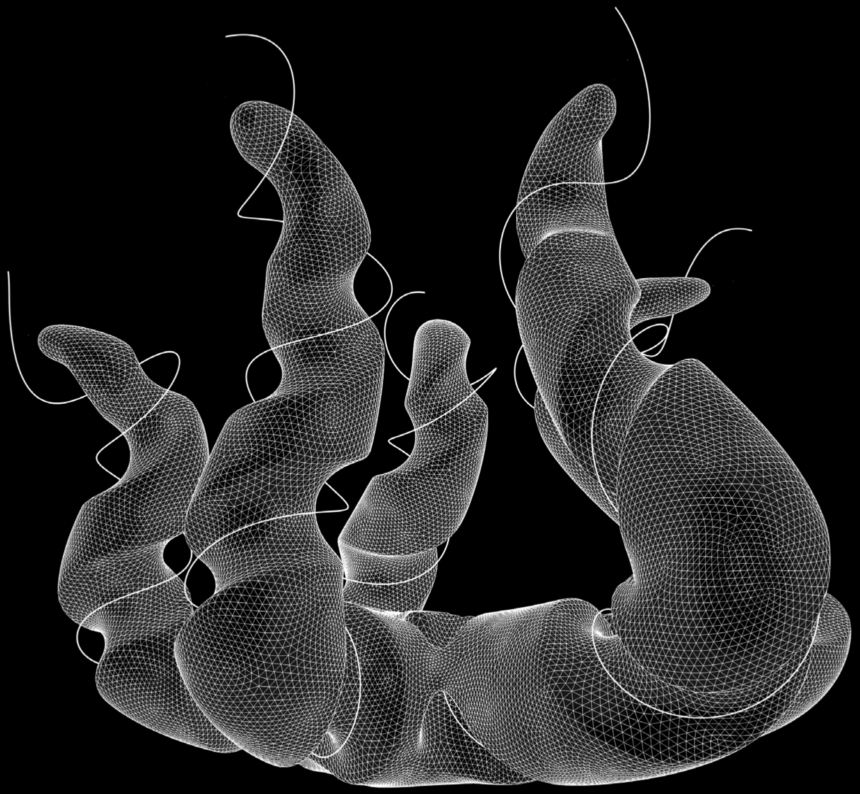
algorithm first manages the intersection locations between multiple struts at a given node through the use of the gift-wrapping convex hulling strategy first described by Preparata and Hong (Preparata and Hong 1977), which produces a triangulated polyhedron that operates as the minimal geometry for intersecting with or enclosing a collection of points in Euclidean Space. It begins by placing polygons of the specified radius normal to the outgoing vector of each strut from each node It then calculates the "worst-case" offset required for generating a convex hull around the vertices of each connection. Here, the angles between each strut end and their respective polygonal radius are considered, wherein the minimum offset for all polygons must be offset by a value great enough for the hull to be convex, ensure planarity for each discrete strut polygon, and maintain connectivity along struts. Once the script has solved the convex hull connectivity at this minimum bounding, it allows for struts to "shrink" toward the centre into non-convex hulls based on the targeted node offset and per-strut calculations of minimum offsets. This allows for only the most acute angles in a node to have significant offsets, and all others may remain relatively tight to the node center. Finally, the struts themselves are meshed, with the two polygonal sections of each strut's end-node stitched together in a hexagonal pattern.

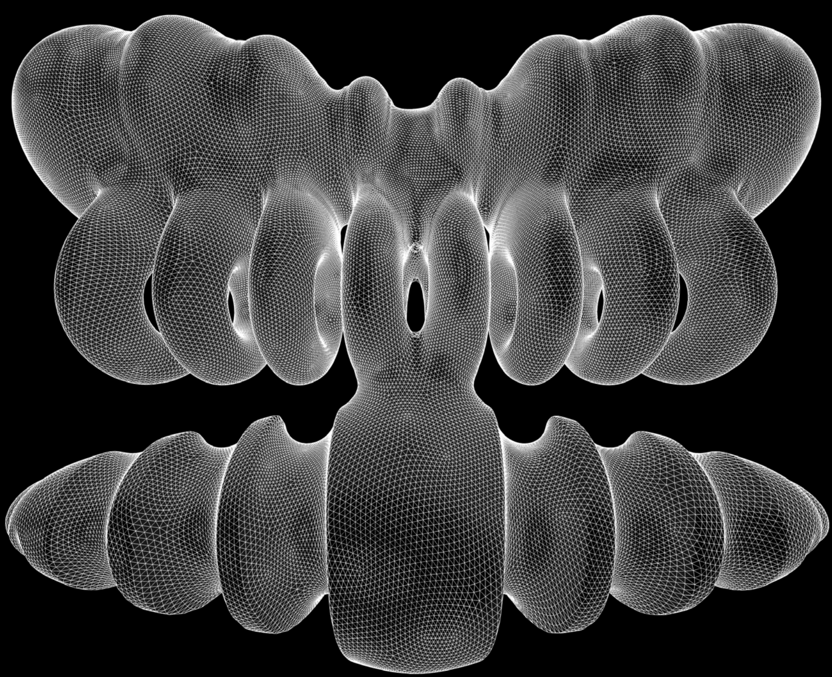
While *Exoskeleton* was developed more purely for its function as a plug-in, its connectivity logic strongly informed the data structure for managing and maintaining connectivity between nodes in *The Rise*. Additionally, the convex hulling strategy used to resolve the nodes here became central to the resolution of the assembly detail for *The ACADIA Rise*, where member connectivity was managed entirely through the mesh topology of convex hulls.

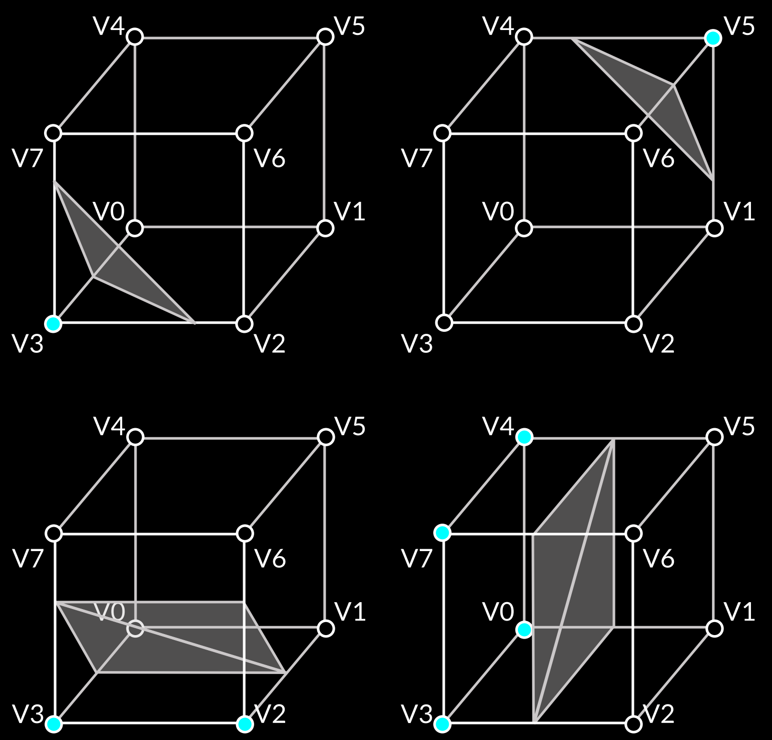
Cocoon

Cocoon is a Grasshopper plug-in (Stasiuk 2015) that implements the well-established marching cubes algorithm originally developed by William E. Lorensen and Harvey E. Cline (Lorensen and Cline 1987). The marching cubes algorithm has been broadly deployed since its introduction more than thirty years ago for the conversion of three-dimensional numerical scalar fields into mesh-based representations.

The algorithm works by discretising a specified volume of space into a grid of points at a specified resolution, and then evaluating the







Figures 10 - 13: (Clockwise from upper left) Examples of the *cubes* within the Marching Cubes algorithm being split according to vertices falling either within or without the scalar threshold. Here the vertices that fall outside are colored cyan. 7 & 8 demonstrate when one vertex alone falls outside the threshold, a single triangle is formed. When more vertices fall outside, as in 9 & 10, additional definitions must be considered. In total, there are 256 possible combinations of vertices falling inside or outside a specified scalar threshold.

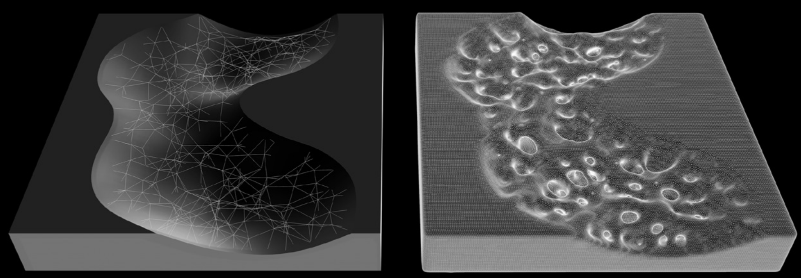


Figure 14: The translation of a Brep and collection of lines into a mesh using *Cocoon*

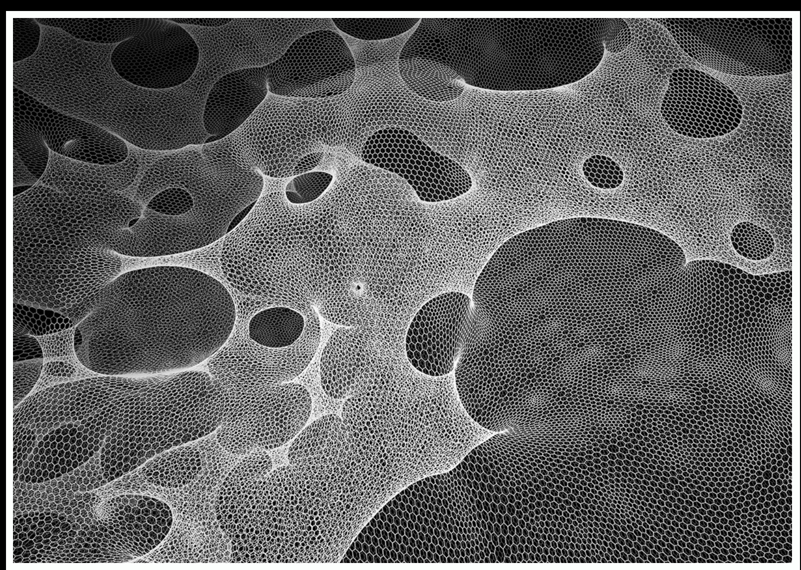
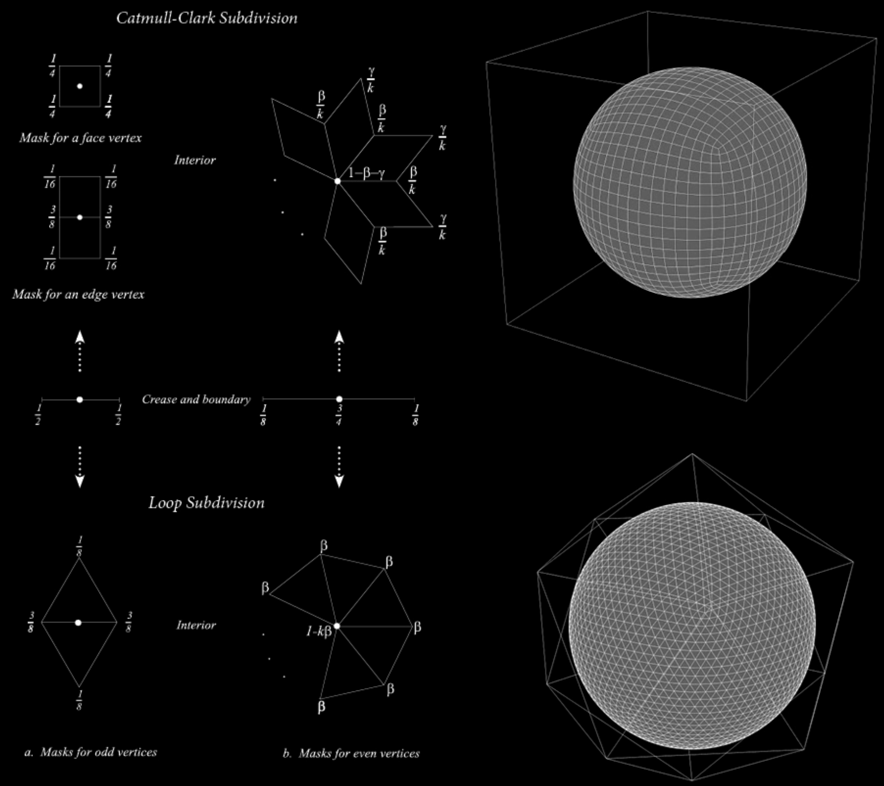


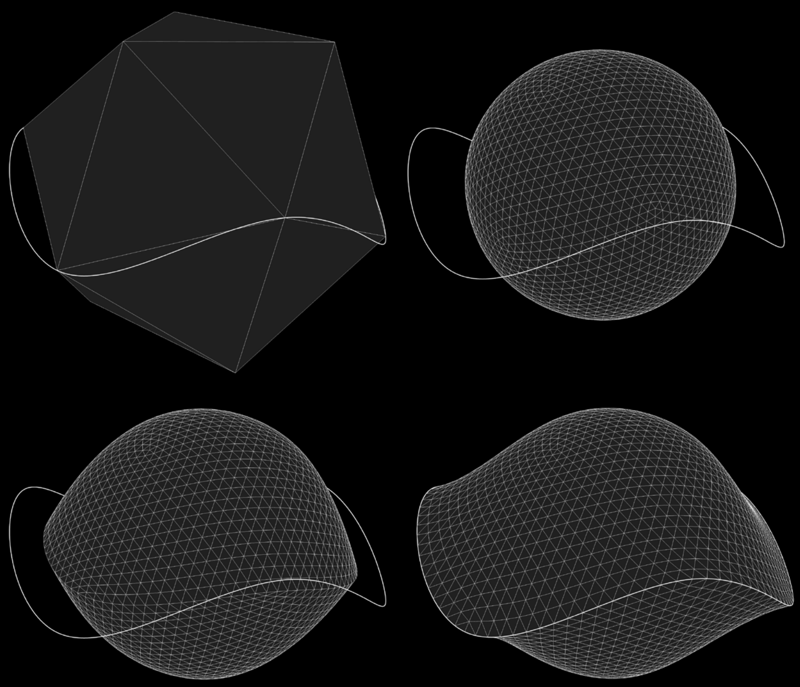
Figure 15: Mesh detail

scalar field at each point in space. This calculation is up to the user to supply, in some way converting the X, Y and Z values of the point to be evaluated into a numerical value. Many Platonic solids may be calculated very directly in this way. Another common approach is to use metaballs, where user-specified points are supplied as inputs, and are additionally parameterised with a *charge* value that informs a distance-dependent decay of influence through a fall-off function. Each point within the grid accumulates a value from each user-supplied metaball. that and charges whose proximity to each point in the grid affects its scalar field value. Based on the specified threshold parameter supplied by the user, the algorithm then slices the spaces between the points within this grid, creating a surface representation based on the thresholds between points that fall *within* the scalar field and those that fall *without*. It achieves this by segmenting the point grid into *cubes* of eight adjacent points. With the scalar value for each point evaluated, the cube of eight points is evaluated against a lookup table that stores all possible combinations of each of the eight points in the cube falling either above or below the splitting value of the field. This table then returns a topology specification that describes how each combination should configure its polygonal slices. Here, the table was taken from Paul Bourke (Bourke 1994).

Cocoon implements this algorithm in a relatively straight-forward manner, but with a specific aim to allow users to parameterise the algorithm directly with geometry supplied in Rhino, rather than mathematically. Here, users can specify point, curve or surface-based objects as geometric drivers, with each supplied with a radius of influence and charge, using the standard metaball fall-off function based on the proximity of each sample point to these elements. *Cocoon* additionally relies on a sparse grid of points for this evaluation, which increases the efficiency of the algorithm in its computational requirements. Whereas more traditional approaches calculate scalar field values for all points within the bounding grid, *Cocoon* limits this computation only to those points that are pre-determined to fall within the radius of influence for each input. Additionally, *Cocoon* allows for the use of *negative* charges, where geometry may be used to specify subtraction rather than addition.

Finally, because the initial meshes produced by the standard Marching Cubes algorithm are necessarily subject to irregular and


Catmull-Clark Subdivision
Mask for a face vertex
Interior
1−β−γ
Mask for an edge vertex
Crease and boundary
Loop Subdivision
Interior
1-kβ
a. Masks for odd vertices
b. Masks for even vertices



uneven topology, *Cocoon* affords users the ability to improve the quality of the mesh by leveraging a series of Euler transformations, smoothing operations, and subdivision that improve the quality of the output mesh for further use in the design supply chain. These Euler operations implement the logic presented in the open-source library Mesh Machine (Piker 2014), and all of the mesh operations managed throughout the process rely on the half-edge mesh library Plankton (Piker and Pearson 2014). Crucially here, because smoothing operations result in mesh vertices being relocated relative to their neighbours, Cocoon follows them with a final relocation operation which ensures that vertices of the output mesh are projected back to their correct location within the scalar field.

Figure 16: (Opposite) Catmull-Clark (top) and Loop (bottom) mesh subdivision algorithms

Like *Exoskeleton*, *Cocoon* was largely developed as a standalone tool, and principally to support my own exploration of the use of half-edge meshes for topological transformation. One of its prototypes, however, was central to the modelling platform for *The Social Weavers*, which relied on scalar field calculations to inform the sculptural forces that guided the overall form. Additionally, another prototype was used to explore an agent-based approach to mesh valence transformation.

Mesh subdivision

When working with meshes to describe complex geometry, it is frequently desirable to start with meshes that are at coarser resolutions, and then to later refine them into more desirable shapes. Many design software packages that are more focused on sculptural modelling work through this method, where a user will define a coarse configuration which will later be smoothed into its final form. Frequently, this is achieved through mesh subdivision, where mesh faces are recursively split into additional elements, and vertices are smoothed into a more organic form, softening edges or other sharp transitions. Two commonly used mesh subdivision algorithms to achieve this are the Loop subdivision technique for triangulated meshes (Loop 1987) and the Catmull-Clark technique for quad-based meshes (Catmull and Clark 1978). Both of these well-established methods have been employed extensively in computer graphics and CAD modelling platforms for some time. In Rhino and Grasshopper, the Weaverbird plug-in (Piacentino 2009) has given users access to implementations of these algorithms. However, these

Figure 17: (Opposite) Application of the Loop subdivision algorithm with specified crease. Clockwise from upper left: a) initial mesh condition with crease curve; b) subdivision with no crease strength; c) subdivision with passive crease; d) subdivision with hard pull to specified crease curve.

implementations lack some important features.

Working across multiple scales of resolution was a central feature of the Stressed Skins experimental project. While much of the mesh layout and analysis was performed at a coarser level of representation, the final geometry – and most crucially, the meshes used to extract toolpaths for robotic forming – required highly refined meshes. Because the panels for Stressed Skins were chiefly planar, and the features robotically worked into them began from this planar condition, it became essential to be able to assert creases into each mesh during subdivision. Existing implementations of subdivision algorithms did not support this, so it became necessary to create a custom implementation that allowed users to specify both anchor points and creases. Again using the Plankton half-edge mesh library, these algorithms were created as Grasshopper definitions following the 2000 Siggraph conference course notes on mesh subdivision (Zorin et al. 2000). Importantly, as new vertices are introduced in each subdivision step, the original mesh vertex mappings are maintained, allowing for analytical results and information related to material specification to be maintained within the final geometric mapping.

Conclusion

This chapter has introduced several of the tools and algorithms that have been both produced and publicly disseminated as a part of this research project. While this output itself has value, it should be seen as a secondary or consequential contribution for the overall PhD project. It is more important here to highlight how engaging within research as part of a digital-material practice – where production and discursive reflection are cultivated through a recursive or catalytic relationship with one another – engenders outputs that may be generalised or re-used in multiple applications.

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Part III: Conclusion

11. Discussion

This dissertation has been presented in two parts. The first has defined the aims, context, motivations and broader theoretical framework within which this research project has been undertaken. It also presented the methodology used in the research project, which also describes a general theory of practice that is here presented as an additional contribution to knowledge. The second part of the dissertation has been presented as a partial research diary in the form of selected, peer-reviewed publications that have been disseminated over the course of the research project. Additionally, it described brief descriptions of selected digital design tools that have been authored as a product of this research project and made freely available to the computational design community. This final chapter aims to reflect on the results of these efforts and re-articulate the principle contributions to the state-of-the-art resulting from the experimental output of this research project. Finally, it will reflect on some of the challenges that were encountered during the project and discuss opportunities for future work through a broader reflection on the role that the ongoing transformation of technology plays in contemporary architectural practice.

11.1 Contributions

This research project has been principally focused on modelling methodology in the building sciences, specifically for computer-aided design activities that privilege computational or algorithmically driven approaches. This interest reflects concerns that I have developed in my own practice, in conjunction with the mutual broader ambitions associated with the broader Complex Modelling project undertaken at the Centre for Information Technology and Architecture (CITA), within which my own research has been embedded. The contributions to methodology that I have endeavoured to undertake reflect manifold interfaces with this concern, engaging advancement in the state-of-the-art for applied computational modelling techniques, while also reflecting on a theory of modelling practice that may be better calibrated to take advantage of the opportunities or leverage the potentials embodied by computation. The contributions presented in this research project are threefold. First, I have defined adaptive parameterisation as a general method for model formulation that enables designers to effectively exploit the unique opportunities afforded by computational design techniques for improved design output, or the increase of design intelligence. Secondly, I have presented the digital-material practice as both the methodology employed throughout this research project, but also as a general theory of practice that engages in constructive design research to integrate artefact design and development with knowledge production and contribution to theoretical discourse. Lastly, a tertiary outcome of this research project has been a collection of publicly disseminated computational plug-ins and tools. In this section, I will review and reflect on each of these contributions.

11.1.1 Adaptive parameterisation

Considering that contemporary architectural design projects are generally developed and realised through collections of inter-related, digitally-situated partial models – what this research project has discussed as model networks – an important concern for research into modelling methodology is how each partial model interfaces with adjacent representations. These thresholds embody the parameter spaces between models, or how they acquire information from the representations on which they rely, and how they pass on the design intelligence they produce to dependent representational engines. Through the experiments undertaken in this research project, adaptive parameterisation has been developed a method of computational model formulation that engages in an applied focus on these parameter spaces that bind partial models to one another. It promotes the development and implementation of data structures that behave as mutable substrates which may be dynamically activated through algorithmic systems.

Experimental implementation

Each of the larger-scale design experiments undertaken in this project has employed modelling systems that have critically engaged model parameter space through a series of several vehicles of inquiry; the modelling methodology I have termed adaptive parameterisation has emerged through this. The vehicles of inquiry that enabled these findings include open topologies, design simulation, the consideration of agency as a continuum, machine learning, and multi-scalar modelling; these have been employed in different degrees within each of the experiments presented in the second part of this dissertation.

Of these vehicles of inquiry, both open topologies and design simulation have been centrally featured within each design experiment. In The Rise, The Social Weavers, and The ACADIA Rise, the application of open topologies and design simulation were central to enhacing feedback loops between morphogenesis, material simulation and assembly specification. Whereas in more traditional modelling setups, the partial models responsible for each of these processes are generally developed in sequence, these three projects pursued the goal of integrating the results of material simulation into the configurational outcome of the model as its form emerged. To do so required the creation of data structures that supported this. This was especially true for The Rise and The ACADIA Rise, where branching nodes needed to capture key relational data between individual growth stages, or modules. These projects employed a custom graph-based data structure that captured relationships between growth modules – for tracking branching relationships – as well as the within each growth module, relative to the design mesh that was employed for the particle-based simulations of bending during growth. Whereas previous research into bi-directional constraints have focused on coupling defined topologies for the design space with algorithmic simulation or activation, here, critically, the data structures employed in these experiments enabled the establishment of multi-directional constraints between elements whose final configuration was unknown. This begins to define adaptive parameterisation in practice, where it allows for open-ended modelling systems to transform their configuration as they emerge, and feed both forward and backward along the design supply chain.

While open topologies and design simulation remain critical concerns for both of the design experiments Learning to be a Vault and Stressed Skins, the interest remained to continue to extend the potential for parameter spaces to begin to exhibit increasingly emergent characteristics. In Learning to be a Vault, this process was explored through the application of machine learning. Here, the data structures that behaved as mutable substrates were deliberately simple: the actual simulations employed to generate the thousands of design options that the project relied on for clustering operations are less sophisticated than those used in the first three experiments. However, the sheer number of design options created presented its own unique challenge for data management, especially in conjunction with their attendant descriptive data reflecting both the performance results used for the multi-objective optimisation algorithms, as well as that used within the clustering algorithm. Here a data dictionary was created, as well as a means to both quickly and flexibly "pack" and "unpack" large volumes of data to and from binary files that were able to interface both with geometric object representation and external machine-learning libraries.

Stressed Skins engaged adaptive parameterisation in its approach to design, develop, analyse and describe material behaviours through multi-scalar modelling. It achieved this through the custom implementation of a half-edge mesh data structure, establishing multi-directional dependencies that enabled the translation of design intelligence between representations. The mesh's performance as a mutable substrate enabled it to effectively describe geometry at different levels of refinement while retaining and passing on critical local material specification data.

In the experimental projects described in this research diary, adaptive parameterisation reflects a methodological focus on underlying data structure for its potential to synthesise multiple partial models within a model network such that it elicits positively holistic performances, where feedback loops and multi-directional constraints compound design intelligence across the supply chain, spanning ideation to installation. Importantly, the data structures employed for each project have more frequently than not differed significantly from one another in their organisation and makeup. While the examples produced through each experiment are presented in hopes that each may support future work and for their general applicability, adaptive parameterisation as a modelling method aims not to be generalisable and therefore useful for a diverse set of approaches. It aims to be prescriptive only in terms of how underlying data structures should perform in support of model practice, rather than specifically in how they should be formulated.

11.1.2 The digital-material practice

As design and modelling technologies become more sophisticated, diverse, and specialised in their descriptive capabilities, it is important to develop methodologies that are suited to take advantage of their potential for engaging open-ended, flexible, and increasingly intelligent systems. While adaptive parameterisation has presented as one approach that aims to help the practical negotiation of this complexity, it also becomes important to engage in ongoing critical reflection of process. This relates not only to model functionality, but also for engaging epistemological concerns about model makeup and the axiological positioning of modelling methods. Pursuant to this is an emerging desire to formulate a model of practice that is well-positioned to support both instrumental and theoretical interests.

As an engagement of these aims, this research project has extended a model of practice that has been presented in this dissertation as the digital-material practice as an action-oriented research methodology that emerges from a well-established tradition of action-oriented research methodologies. This is an explicit evolution to Stan Allen's material practice, adopted within the framework of CITA's established approaches to experimental practice, where probes, prototypes, and demonstrators are fashioned as engines for inquiry into architectural design practice. Material practices promote a catalytic relationship between design production and discursive reflection. The digital-material practice specifically privileges experimental frameworks in this context, and additionally considers digital modelling processes as valuable targets of epistemological inquiry. It engages experiments across multiple scales and intentions, ranging from larger experimental projects to small, one-off design probes or inquiries.

11.1.3 Digital instrumentation

The larger experiments and the research diary comprised of their associated publications have provide theoretical and practical knowledge mappings for negotiating complexity in model formulation and project delivery; and the digital-material practice has presented a theory of practice that is well-suited to address the increasing variety of emergent technologies and concerns that attend them. Lastly, the digital instruments described in the previous chapter reflect a small but important contribution resulting from this research project. Their value is manifold. First, they reflect freely available tools for improving the modelling capabilities of the computational design community, and in that role have been downloaded and used extensively. Secondly, and perhaps more importantly here, having emerged as supporting experiments within the larger experiments that comprise the principal body of this research project, these instruments stand as demonstrators regarding the utility of the digital-material practice. The engagement in their development as stand-alone tools generalises their capabilities and encapsulates important components of experimental findings for application elsewhere. It reflects the catalytic relationship between action and discourse that is central to digital-material practices.

11.2 Toward practice

I will conclude this dissertation with a few thoughts in consideration for the limitations and failures I encountered while undergoing this project, what next steps these limitations and my successes suggest, and thoughts for how this research may map forward into professional practices.

11.2.1 Limitations

For model networks, parameter spaces organise initial conditions and supply the algorithmic elements of a design model with on-going references for thresholds and dimensionality and for keying the execution of the model's code-driven decisions. Variations of parameter values as both input and output empower the designer to interrogate model networks and test or leverage whatever capacities it may have for design exploration, optimisation, versioning, or localised deployment. Such second-order, procedurally-driven modelling become a means for generating new architectural information. Yet these parameter spaces are nearly always explicitly bounded by the designer. One of the driving motivations for this research project was to produce a means to author emergent parameter spaces, whereby features would not only be adaptable or variable in number and configuration, but that they would demonstrate some means of epistemic autonomy in their formulation. Adaptive parameterisation has been successful in creating mutable data structures, but it remains that their initial setups are explicitly bounded by the designer.

The elusive nature of emergent parameterisation

In the field of robotics, there has been a great deal of success by such researchers as Hod Lipson in the application of evolutionary solvers for both morphogenesis and behavioural instruction development. He has worked on multiple projects where robots are conceptualised and "evolved" through the use of such generative processes as those enacted through stochastic l-systems. (Bongard, Zykov, and Lipson 2006; Clune, Mouret, and Lipson 2013; Hornby, Lipson, and Pollack 2001) These l-systems are essentially algorithms that define the shape and function of various components of a robot. With a particular target for performance optimisation established – in the case of these robots, the fitness target is generally related to efficiency or robustness of locomotion – and a particular set of ingredients available for the l-system to use, the mechanisms he and his teams establish activate the model through the application of evolutionary algorithms to dynamically write sequences to feed the l-system for morphogenesis and behavioural instruction. This may be interpreted as a direct procedure for activating the emergence of new dimensionality in a feature space. It is, in a sense, the parameter space being empowered to directly invade the algorithm through the process of altering the instructions it gives, and actively learning how to do it better, in an ongoing fashion. While adaptive parameterisation allows for the parameter space to adapt to changes made by the algorithms within each partial model it binds together, it does not explicitly exert any opinion not in some fashion pre-configured by the designer. Future work in this field could further examine means to enable the feature space itself to undergo its own evolutionary processes.

Model fragility

Another aim for this research had been to promote modelling methods that supported increasingly robust or resilient computational models. Yet the well-documented problem of model fragility (Davis 2013) persists. While adaptive parameterisation helps to create more flexible modelling environments, and its approach to developing data substrates that enable partial models within a network to share critical information can help ensure that individual partial models may more reliably interface with one another, even these computational models are prone to having to be reset or rebuilt from the "botton-up" if some fundamentally new constraint is introduced into the modelling environment. In this light, it is fair to acknowledge that complex modelling is just that: if there is any magic bullet that will dramatically simplify computational modelling setups, then adaptive parameterisation as a methodology is not it. However, in this same vein, it perhaps may be argued that simplicity is not the point.

11.2.2 Research in practice

Both before and after my pursuit of this research project, I have worked as a consultant in the Architecture, Engineering and Construction industries, most prominently supporting the development and deployment of advanced digital modelling practices. Here I have worked in various roles: in some projects I have been directly embedded as a lead digital modeller, resolving complex geometries, detailing and assemblies for various projects; at other times I have been more indirectly involved, authoring and deploying plug-ins, add-ons, or other algorithms that have enabled clients to extend or enhance their own capabilities for automation, geometry authoring, managing interoperability, or otherwise asserting greater control over data labelling and information capture; additionally, I have worked to help .

Between my involvement in the Complex Modelling project at CITA and through these experiences, I have become acutely aware of some of the gulfs that exists between the avant-garde of architectural design modelling research and the daily reality of most professional architectural practice. In a modest way, this research project aims to bridge parts of this gulf.

Engaging flexibility

Within any given project, where partial models are expected to communicate with one another, a consistent or shared data structure for passing key design data between partial models within a network appears desirable: it suggests stability and allows that any procedural changes activated locally within a particular partial model will not break its fundamental relationship with its interdependencies, because though its internal computational logic may shift, its protocol for interacting with its adjacencies will persist. Adaptive parameterisation presents a method for addressing this interest, which is namely for the modelling team to develop an understanding of the underlying data requirements to effectively parameterise each partial model within the network, and formulate or implement data structures that support open-ended design systems that may be activated through bi- or multi-directional constraints.

In the introduction to this dissertation, I discussed the ongoing proliferation of new design technologies that affords designers and other stakeholders in the building sciences opportunities to extend their modelling capabilities. The availability of APIs, SDKs, and integrated Visual Programming platforms within popular and affordable CAD modelling software enables third party developers to invent new approaches or better implement existing algorithms that may have previously been difficult for designers to employ, delivering increasingly specialised methods and more highly resolved analytical insights to target systems of interest. However, efforts to leverage this continuously expanding array of design systems is attended by an increase in model complexity: as the sophistication of output is extended and connectivity between partial models becomes more numerous, negotiating the information exchange between adjacent or dependent models and representations becomes simultaneously more important and difficult. This challenge has frequently been defined as one of interoperability, or the means by which one software platform or model setup exchanges information with others. In professional practice, many contemporary approaches to interoperability rely on strict file-based protocols, such as the Industry Foundation Classes for building information modelling or CIS/2 for steel specification. While these approaches may be effective for many more basic data exchange operations, and even highly appropriate for data archiving and documentation, their relative inflexibility may make them ill-suited to use as information substrates for translating data that does not easily fit highly prescriptive structures. And indeed, many other interfaces between partial models are not managed in any way at all: it is perhaps even more likely that a stakeholder in the supply chain will simply re-create a new model "by hand" from a dependency entirely from the ground-up, replicating the geometry through measurement and duplication.

This research project presents a critical response to such "hand-tooled" or protocol-based approaches, highlighting their relative inflexibility, especially regarding the larger-scale application of multi-directional constraints or sophisticated feedback loops between partial models in broader networks. These frameworks have been discussed as being *homogenising* in their makeup, aiming to unify modelling systems through a normalisation that privileges a specific data format over its utility or relevance to the problem at hand. Here, adaptive parameterisation has been presented as an alternative means to design and leverage more open-ended or customisable data structures to best maximise the potential of the opportunities afforded by emerging computational modelling techniques.

And the experiments that have been presented in this research diary work as demonstrators for adaptive parameterisation as a method for model formulation, and a contextual proof for the digital-material practice. However, it must be acknowledged that the nature of the experiments undertaken here differ significantly from those encountered in professional practice, in both scale and constraint. Although I understand that much of this research must be considered base research in that it does not need to justify itself for its applied value in professional practice, I believe it is nonetheless important to explore opportunities to map knowledge frameworks from research into professional practice.

This is also especially important when we consider that the same proliferation of design technologies that is driving certain practices toward normalising protocols is fueling what has been described as manifold and ongoing "crises" in architectural modelling. Those previously described include: a fundamental distrust of digital design tools for their inability to adequately capture or express complex design intent, as Brian Lawson asserts (Lawson 2002); a concern that technological advancement, rather than enabling architects to more closely embed material considerations into the tectonics of their designs is instead accelerating the alienation of complex geometry from underlying matter (Oxman 2010); the enervation of heuristic or embedded understanding of performance concerns due to "black box" computational solutions that obscure solution logics from designer intuitions (Turkle et al. 2009); and a inundation of complication and redundancy introduced through the parallel implementation of multiple technologies that fail to be properly integrated with one another (Eastman et al. 2011). This short list is also woefully incomplete: between academia and professional practitioners, there is an endless train of new crises to consider when it comes to technological implementation in practice.

It is not immediately clear that there is a satisfactory answer to these concerns, nor that there will ever be one. What does seem clear is that technological solutions and design systems will continue to proliferate, increasing in both number and specialisation, and that finding strategies to effectively understand them and reconcile their heterogeneous nature with one another may be a productive means to not only move forward, but to best take advantage of the increases in design intelligence such systems afford their users. It is in this I have aimed to present a flexible and generalisable methodology that is not explicitly prescriptive in the application of any single underlying data format, but rather focuses the designer attention on the information thresholds that bind what are now necessarily are wide range of representations that will be deployed within projects of even modest complexity.

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