Computation and Material Practice in Architecture: Intersecting Intention and Execution during Design Development

An exegesis submitted in partial fulfilment of the requirements for the degree of Doctor of Philosophy

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August 2011
Declaration

I certify that except where due acknowledgement has been made, the work is that of the author alone; the work has not been submitted previously, in whole or in part, to qualify for any other academic award; the content of the thesis is the result of work which has been carried out since the official commencement date of the approved research program; any editorial work, paid or unpaid, carried out by a third party is acknowledged; and, ethics procedures and guidelines have been followed.

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August 30th 2011

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Acknowledgements

My experiences throughout the duration of my candidature, and the research I have generated, owe a substantial debt of gratitude to many people at RMIT University, Melbourne, Australia. Particularly those who have been part of the ‘research family’ at the Spatial Information Architecture Laboratory (SIAL) and my collaborators at the Innovative Structures Group (ISG). I am particularly grateful to my senior supervisor, Professor Mark Burry for the opportunity to conduct this research, and for his continuing support, insight and guidance. I am also exceptionally thankful to Professor Mike Xie whom has supported and encouraged the technical aspects of this work with unwavering dedication and enthusiasm.

Further thanks must go to Yi Yi Zhou [aka Tommy Tensegrity] who has been a close collaborator and ‘partner in crime’ during the latter parts of the project work and enabled technical research into tensegrity structures with 3D compression members to advance at an exceptionally fast pace.

Special acknowledgement to architect and educator Philip Beesley who serendipitously enabled a significant advancement of my research when he transferred two folders titled ‘Tensegrity’ to my memory stick at the ACADIA conference in October 2008. The folders were from the computer of the late Dr. Thomas Seebohm who had very recently passed away while happily cycling in Knowlton, Quebec.

Sincere gratitude to my second supervisor Juliette Peers and also Susu Nousala, who have both taken time out from their own busy schedules to read, comment upon and edit various aspects of this work, and without whom this exegesis might never have made it to print.

A final thank you to those who have listened to my rants, given me feedback, supported and fed me over the last few years. In particular my ‘extended’ family; Antoninio el duende loco, Estonella, Catie Cakes, May-B, Victor Holder and the many others that orbit La Favella del Eagle.

Extra special thanks to Sam ‘Wise’ Zylberberg whose unwavering dedication got me over the line, muchas gracias to Julian ‘Aguardiente’ Clavijo who did a superb job of laying out this document, and a final thanks to Flora ‘Étoiles plein les yeux’ Vourron who supported me in my darkest hours.

To conclude, I feel that an apology should be made to those people whom I have gradually drifted away from as the pressure of this task has mounted. I hope to overhaul my communication skills and re-integrate with all you lovely people upon completion.
Abstract

It is generally believed that computation and computer numerical control (CNC) manufacturing technologies empower architects by enabling better integrated architectural design to production processes. While this is a tantalizing prospect, there is no clear strategy in place for achieving this goal. Furthermore, the extent to which design, engineering and construction might be integrated around digital technologies is currently limited as the computational processes architects use for design exploration are not typically informed by material logic and the logistics of materialisation.

My research explores whether computation and CNC manufacturing can support more informed design methods and better integrated production processes in architecture. I identify the critical factors involved in pursuing this goal and elaborate on an integral computational methodology capable of enhancing the bond between designing and making. My hypothesis is that digitally mediated design and manufacturing can strengthen the relationship between intention and execution by enabling closer engagement with fabrication during early design exploration, and by supporting more informed decision making via dynamic design representations with embedded material intelligence.

This hypothesis has been developed and tested through project led research. Although varied in nature, the three investigations I have undertaken serve as complimentary vehicles of discovery and evidence for my claims. Each investigation was devised and carried out in response to practical observations, a critical review of literature focusing on historical and contemporary relationships between design and construction, and a series of precedent studies related to materially informed design computing.

As a group they contribute to understanding how digital technologies might be employed by architects to enhance and expand design to production processes, and shed light on some of the technical, cultural and philosophical implications of a deeper engagement with materials and processes of making within the discipline of architecture.

My research concludes that new kinds of interactive simulation and evaluation tools, coupled with access to digital fabrication technologies, enables an accelerated generation, evaluation and calibration process during early design exploration. This mutually informed digital-material feedback loop makes it possible to rapidly develop acute material intuition. Heightened material understanding can, in turn, facilitate new kinds of architectural systems and materialisation strategies which could lead to better use of available resources, more innovative design and a stronger bond between intent and outcome through more streamlined design to production processes.

The digitally supported materially informed methodology that I outline encourages a shift in design process and attitude, away from a visually driven mode of architectural composition towards material practice - an approach in which the self-organising logic of materials and the logistics of materialisation are used to actively inform design exploration, refinement and construction processes.

My project based outcomes, findings and observations prompt re-evaluation of the conventional distance between architects and processes of making by highlighting the importance of deep material engagement and broad practical knowledge when utilising computation and CNC manufacturing technologies for designing and producing architecture.
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CHAPTER ONE

1.1 Introduction
1.2 Background
1.3 Research Problem and Question
1.4 Aim
1.5 Motivation
1.6 Research Method
1.7 Exegesis Structure
1.1 Introduction

My research explores the extent to which computation and CNC manufacturing can support more informed design methods and better integrated production processes in architecture. My central proposition is that digitally mediated design and manufacturing can strengthen the relationship between intention (design) and execution (construction) by facilitating a rapid digital-material feedback loop during early design exploration, and by supporting more informed decision making via dynamic design representations with embedded material intelligence.

My thesis has been developed through three sets of practical investigations, each of which have explored ways of intersecting computational design, engineering analysis and processes of making during the conceptual design phase in architecture. The applied research component has been supported by a critical review of literature focussing on historical and contemporary relationships between design and construction, and a series of precedent studies related to materially informed design computing.

Over the course of my candidature, the findings and outcomes from this research have been presented at a number of conferences, published in a series of peer reviewed articles and exhibited in both local and international contexts ¹.

1. See appendix for details and full articles

1.2 Background

Today’s construction industries are organised around a distinction between people who design buildings and people who construct them. Whilst this division of labour has proven advantageous in many respects, a linear model of building practice, in which an architect designs, an engineer analyses and a builder constructs, has prompted a convention in which “construction insight is wholly missing from the conceptualization of the design, and design insight is applied only sparingly during its execution”[Bernstein 2010: 194].

Since the turn of the millennium, it has become increasingly apparent that powerful computer aided design, analysis, optimisation and manufacturing tools may offer a way to address this issue. An example of the current state of discourse can be found in a set of notes accompanying a lecture by architectural theorist Branko Kolarevic, where he distils what could be considered one of the central tenets of the architectural avant-garde:

“By integrating design, analysis, manufacture, and the assembly of buildings around digital technologies, architects, engineers and builders have an opportunity to fundamentally redefine the relationships between conception and production. The currently separate professional realms of architecture, engineering and construction can be integrated into a relatively seamless digital collaborative enterprise – a digital praxis”[Kolarevic 2006: 2-3]².

Architect and educator Scott Marble suggests that this possibility arises because "CNC systems put the process of design closer to the production of buildings, merging production and design into a common language of digital information" [Marble 2010: 40]. Robert Stern observes that consequently, "the computer has the potential to expand the professional’s control over the world of built form by linking designers with constructors more closely than since the dawn of the machine production" [Stern 2010: 15].

While these comments suggest tantalising prospects for architects, in practice there remain questions around how computation and CNC manufacturing might be specifically engaged and strategically leveraged to enhance and expand the relationship between architectural design and construction. Phillip Bernstein suggests that "attempts to close (the) gap between intention and execution are at the root of current innovation catalyzed by the more extensive use of digital tools and processes" [Bernstein 2010: 194]. My research explores this territory and contributes to the emerging discussion.

1.3 Research Problem and Question

Over the last decade, there have been increasing claims that computation and CNC manufacturing technologies are of interest within the discipline of architecture not only for their capacity to facilitate expressive forms, but also and perhaps more importantly, because they allow architects to "generate construction information directly from design information through the new processes and techniques of digital design and production" [Kolarevic: v].

It is thought that a higher degree of control over design and production information, coupled with customisable ‘file to factory’ processes, will facilitate a range of new spatial, formal, performative and methodological possibilities in architecture. Whilst these ideas seem reasonable in theory and have been partially implemented in practice, the extent to which this territory can be fully explored and potentially expanded is currently limited. The reason for this is that commercially available design software typically allows geometry to be constructed independently from material and structural considerations. This situation often leads to "a sculpturally driven design process where the translation of form into buildable components is developed after establishing the form" [Kilian 2006: 38].

While conventional CAD tools can be used to generate astonishing spatial compositions with great ease, "they frequently lack the informed discipline of ... integration with engineering, along with their translation into fabrications and constructions" [Schodek et al 2005: 35]. As a result, "digital 3-D models, created to convince clients and constructors, tend to neglect manufacturing ... and feasibility" [Aigner and Breit-Cokcan 2009:434].

There are two dimensions to this problem. The first is technical and related to the overly abstracted nature of digital design processes and representations. The second is more cultural and pertains to both the linearity of building practices and a lack of practical knowledge on behalf of architects. The question these issues raise is:

*What kinds of 3D digital modelling tools might support more informed decision making and facilitate a deeper understanding of practical construction issues and potentials during early design exploration?*
A helpful way of elaborating on this research question is to consider the difference between alternate ‘generations’ of design software. According to Cristiano Ceccato, first and second generation tools (2D drafting, conventional 3D modelling, parametric and building information modelling) typically emulate activities that can otherwise be done manually (Ceccato 2001: 3). He advances the idea of a third generation of architectural design software that promotes a new kind of reciprocal relationship “where the designer and computer form a partnership of compliments, each contributing specific abilities and knowledge to the overall task of architecture” (Ibid). He argues that embedding design ‘intelligence’ within digital representations, “in the form of rules, gestures, goals and parameters” (Ibid: 4), will help to achieve this goal.

1.4 Aim

In light of Ceccato’s distinction and the contemporary interest in pursuing more informed and better integrated architectural design to production strategies, this research can be described as being focussed on identifying ‘third generation’ digital methodologies capable of supporting an approach to design informed by material, structural and assembly logics. The aim therefore is to explore the extent to which computation and CNC manufacturing might allow construction insight to become an active driver during early design exploration, and whether this mode of practice could lead to new architectural possibilities and a stronger relationship between design intent and built outcome.

1.5 Motivation

A Personal Perspective

Since commencing my architectural education in 1999, I have always found it puzzling that building design – a task intrinsically tied to the material world – often prioritises visualisation over materialisation during the early design phase (Ceccato 2001, Leach 2004, Oxman & Oxman 2010, Weinand and Hudert 2010). This visually oriented design attitude was reflected in my own early architectural education, which focussed less on the science of materials and making, and more on the art of ideation and drawing.

The disjunction between processes of design and construction in architecture had raised questions in my mind around how buildings could be artfully conceived without a practical understanding of making or materials. Experience designing domestic architecture and working for firms in Sydney and Melbourne has since revealed that this perplexing situation is infrequently queried in normative architectural design and construction practices.

In my second year of study, I became interested in and familiar with sophisticated ‘second generation’ 3D modelling software. I observed that although the infinite pliancy of virtual geometry opens architectural design to a range of new and exciting formal and spatial possibilities, a lack of practical construction knowledge limits the degree to which such tools can be meaningfully explored and engaged by architects. While I was able to develop complex geometrical forms in the computer with ease, I had no mechanism in place to tell whether they would be structurally plausible and no way of physically testing them.
At the time (2002), my learning institution (UNSW, Sydney) was not set up to support deep exploration of this territory. This prompted me to transfer my undergraduate degree to RMIT University, Melbourne where the computationally focussed Spatial Information Architecture Laboratory (SIAL) was located. In 2003, I became involved in producing scale models of Tom Kovac’s World Trade Center (WTC) proposal and Digital Design Gallery for the Non-Standard Architectures (NSA) exhibition. Both design propositions were developed using sophisticated 3d modelling techniques and were constructed using a contour based CNC fabrication method. The complexity of their geometry meant that they could not be easily fabricated without the use of CNC processes.

This experience provided an exciting, new and a distinctly more hands-on approach to architecture than the one I was used to. At the same time, I wondered whether the visually sculpted WTC form was in fact a plausible architectural proposition. The fact that the geometry was generated without considering materiality and had not been analysed for structural integrity, led me think about the possibility of constraining the digital design process according to specific material, structural and assembly logics. If this could be achieved, architectural forms created in a virtual environment would be inherently rational and buildable.

An example of such an approach is Surface Evolver, a computational tool I discovered during my undergraduate degree that simulates the behaviour of minimal surfaces. By constraining parts of an initial geometry, it is possible to generate virtual shapes that approximate physical funicular formations. The results can be easily calibrated against physical models and correspond to architectural forms that can be constructed using tensile membrane, cable-net or pneumatic structures.

The notion of achieving a direct and intimate connection between digital and physical media is further enhanced by the possibility that digital fabrication methods support a “direct link from design through to construction” (Kolarevic 2003: 4). In theory, this means that computation can be used to develop expressive yet physically plausible forms, while CNC manufacturing can be employed to produce them.

At the conclusion of my degree in 2005, my engagement with these ideas was limited and had not been properly explored within my practice. In the following years I continued to actively explore this territory as lab technician and teaching assistant at SIAL. Since then I have been involved in delivering eighteen different design subjects across leading institutions in Melbourne and overseas. These subjects have aimed to introduce students to mechanisms for reaching beyond normative architectural practices by exploring digital approaches to integrating synthesis, analysis and materialisation during early design exploration.

Whilst teaching has provided a way of exploring and testing this approach within an educational environment, I have pursued a similar methodology in practice as a co-director of Mesne design studio, a research based atelier formed by Dr. Paul Nicholas and Tim Schork in 2005. This position has allowed implementation of the above ideas to a point, however the conventions, complexity and pressures of ‘live’ architectural practice have limited the extent to which I have been able to fully explore and execute new digital methodologies.

This purpose of undertaking this PhD research is therefore to investigate an integrated, digitally assisted and materially informed architectural design to production process more fully than has been possible in both my teaching and practice.
Co-rational Design

In conventional design and construction practices there are “two general process mechanisms evident – the pre-rational approach and the post-rational approach” [De Silva 2008: 1849]. The notion of facilitating better architectural design to production through an integrated digital workflow raises the possibility of a third alternate methodology that is described in literature as a co-rational approach [Schlueter & Bonwetsch 2006, De Silva 2008, Fischer 2008].

Pre-rationalisation refers to a design process in which an engineered structural solution precedes architectural form [De Silva 2005]. In the context of architectural design, this involves “considering the constructive system... before the actual design process” [Schlueter & Bonwetsch 2006: 202]. Alternatively, post-rationalisation describes the “retroactive fitting of a construction system onto an existing design” [Schlueter & Bonwetsch 2006: 202]. “In a post-rational design process architectural form finding precedes the engineering design process” [De Silva 2008: 1849]. In other words, “the formal design is conceived in a process that is for the most part divorced from considerations about construction” [Loukissas 2003: 32]. This is probably the most common practice today [De Silva 2008].

The pre-rational approach is limiting for designers as it requires that a building adhere to a defined set of geometric constraints [Attar et al 2009: 242]. Pre-rationalisation is thus seldom used in practice [De Silva 2008]. On the other hand, while enabling a certain amount of creative latitude during the conceptual design phase, post-rationalisation results in a significant amount of compromise and antagonism as it puts both architects and engineers in a reactive mode [De Silva 2008].

Co-rationalisation is an emerging trans-disciplinary strategy that strives to optimise structural, material and assembly logics concurrently with design exploration and refinement [Schlueter & Bonwetsch 2006, Fischer 2008]. The basic premise of a co-rational design approach is that the system and logic of construction “is defined alongside and to some extent through the process of designing a form” [Fischer 2005: 2]. De Silva notes that “the co-rational design approach, which seems to be the future trend in the building industry, is more synergistic, encouraging the optimal outcome for stakeholders” [De Silva 2008: 1849].

In theory, the consequences of co-rational design are numerous and include [but are not limited to]:
- Less antagonism between architects, engineers and contractors as manufacturing and feasibility constraints are used to actively drive design process
- A tighter link between design intent and built outcome
- More efficient use of resources via negotiation and optimisation of multiple performative criteria during early design exploration.
- A higher degree of coherence between form, function, structure and ornamentation

While these are attractive prospects for all parties, there are a limited number of satisfactory ways of engaging co-rationalisation from a design perspective. This gap is primarily due to software limitations, interoperability issues and the cultural conventions inherent to the AEC industries. My research is thus motivated by a will to identify and implement digital tools, techniques and methodologies capable of supporting a flexible co-rational approach to architectural design.
1.6 Research Method

Introduction

Investigating the extent to which computation and CNC manufacturing might support better design to production processes implies an applied research method. For this reason my research has been structured around three sets of practical investigations and presented for examination as a PhD by project.

Upon initiating this research in 2007, my assumption, based on literature and both my experience and inexperience, was that digital technologies could potentially address the gap between intention and execution in architecture by facilitating a “direct link from design through to construction” (Kolarevic 2003: 4).

In testing and moving beyond this assumption, my research has not adhered to one particular technique or process. Instead, it has been allowed to evolve through three diverse practical investigations that have each made unique contributions to enhancing my understanding of how digital technologies might strengthen the relationship between design and production in architecture.

To situate and inform my applied investigations, I have simultaneously undertaken a literature review exploring historical and contemporary relationships between design and construction in architecture, and carried out a series of precedent studies related to materially informed performance-based design computing.

Action Research

In conducting this investigation I have employed an approach described in literature as action research. This family of research methodologies pursue action and research at the same time. Bob Dick suggests that, “in most of its forms it does this by using a cyclic or spiral process which alternates between action and critical reflection” (Dick 1999: np). With action research, methods, data and interpretive capacity are refined in light of the knowledge developed and understandings gained in earlier cycles. Dick concludes that action research is “an emergent process which takes shape as understanding increases; it is an iterative process which converges towards a better understanding of what happens” (Ibid).

In The Handbook of Action Research: Participative Inquiry and Practice (2001), the editors explain, “good action research emerges over time in an evolutionary and developmental process, as individuals develop skills of inquiry... [it] leads not just to new practical knowledge but to new abilities to create knowledge. In action research knowledge is a living, evolving process of coming to know rooted in everyday experience; it is a verb rather than a noun” (Reason and Bradbury 2001: 2).

Reflecting these comments, rather than structuring my research around a predetermined series of projects, each of my applied investigations has been devised and carried out in response to findings and reflections from prior practical work and complimentary theoretical explorations. This approach has allowed me to move beyond my original assumptions and ideas, in order to achieve an unexpected series of outcomes and insights that address my inquiry in a more comprehensive manner than I could have imagined prior to undertaking this research.
Reflection in Action

To compliment my action research methodology, I have also drawn upon Donald Schon’s concept of reflection-in-action. With this idea, Schon gives us a means to collapse the distance between action and reflection. This is a particularly useful tool for immersive and complex practices such as architectural design, which hinge on rapid yet informed decision making - or a capacity to ‘think’ and ‘do’ simultaneously.

Schon describes, “when someone reflects-in-action, he becomes a researcher in the practice context... He does not keep means and ends separate, but defines them interactively as he frames a problematic situation. He does not separate thinking from doing, ratiocinating his way to a decision which he must later convert to action. Because his experimenting is a kind of action, implementation is built into his inquiry” [Schon 1983: 68-69].

Considering that my project work is focussed on pursuing better integrated design to production strategies in architecture, the notion of bridging the division between thinking and doing - between the virtual world of ideas and the tangible world of materials - acts as a powerful metaphor for my applied research.

Furthermore, awareness of Schon’s concept enabled me to identify and critically analyse findings and insights from my actions and outcomes while I was engaged in executing and producing them. The semi-structured nature of my applied research and action research methodology allowed me to immediately feed this tacit and explicit knowledge back into future experimentation and implementation.

In the conventional action research process described in Figure 1.6a, theory, practice and reflective analysis are shown as distinct and consecutive phases of research. In considering my personal research journey, I became aware that combining an action research methodology with Schon’s concept of reflection-in-action, prompted a reflective mode of ‘active’ research in which the elements of theory, practice and reflection are considered simultaneously and mutually inform each other. Figure 1.6b is therefore offered as a way of representing the evolutionary and concurrent nature of my research and reflections. The important difference between the conventional action research diagram and my [re]interpreted version, is that my diagram more closely reflects the complex, nonlinear and highly integrated nature of doing meaningful action research.
Collaborations

As I have already mentioned, my research has been structured around three sets of practical investigations. In undertaking this project led research, I have specifically sought to engage with disciplines that could enrich my design outcomes and help me discover new ways of informing architectural design through an understanding of materials and processes of making. Consequently, I have collaborated extensively with engineers, manufacturers and artists as a means to further develop and implement my design ideas. These collaborations have served to facilitate and enrich my applied investigations.

To begin testing my initial assumptions and unravelling the territory in question, Investigation A embarked on a process of manufacturing a series of jewellery objects using a combination of digital modelling, additive fabrication and traditional metal casting techniques. This process required close interaction with Queensland based 3D printing bureau Facet Manufacturing (now FacetRP), and Melbourne based jewellery manufacturers Lenrose Pty Ltd. This ongoing exploration has since been extended through collaboration with Melbourne based multimedia artist Victor Holder.

In attempting to explore a similar production logic at the scale of an architectural component, Investigation B sought collaboration with members of the Innovative Structures Group (ISG) at RMIT University. Since the early 1990’s the ISG has played a leading role internationally in theoretical and practical application of topology optimisation in architecture and design. Topology optimisation is the generic term for a family of computational processes that make use of Finite Element Analysis (FEA) to determine materially efficient structural forms based on applied physical loads and constraints. Collaboration with the ISG was established because Investigation A revealed that design tools informed by logics related to materials and materialisation may facilitate more informed and better integrated design to production.

My collaborative work with the ISG extended into Investigation C, where close work with Dr. Yi Yi Zhou enabled the rapid design, development and assembly of a unique class of prestressed truss. The architectural applicability of these structures was tested through a series of in-house, university-based projects, as well as two practice-based collaborative ventures. These ‘live’ projects include a signage tower for a prominent local developer, and a visual barrier as part of an urban infrastructure intervention. In both cases, it was necessary to collaborate with all key stakeholders, including clients, engineers, builders, other designers and urban planners.

Tools, Techniques and Technologies

To conduct this research I have engaged directly with a range of computational design tools and become familiar with a number of digital and analogue fabrication processes.

• Investigation A - From Conception to Production

At the outset of this research, I believed that the imminent release of large-scale additive fabrication could revolutionise architectural design to production by facilitating the direct construction of infinitely complex architectural forms without the difficulty of complicated representations and potential misinterpretation. Since large-scale technologies are still in development but operate in a more or less analogous manner to smaller scale commercially available technologies, I reasoned that working with additive fabrication at a more manageable scale could still reveal important insights for architectural design and production. Investigation A therefore embarked on a process of designing and producing a series of jewellery pieces using additive fabrication and traditional metal casting.

8. The ISG is an initiative of Professor Mike Xie of RMIT University and Peter Felicetti of Felicetti Pty Ltd Consulting Engineers. It brings together experts in structural engineering and architecture as a means of enhancing collaboration and innovation towards transdisciplinary design.
A minimal surface generator called *Surface Evolver* is used to develop initial forms. Outcomes are imported into *Rhinoceros™* for design refinement. *Geomagics™* is utilised to ensure fabrication feasibility of the final objects. The additive technologies I tested and employed for this investigation were: 3D Systems 'Thermojet', Solidscape ‘t66’, Objet ‘Eden’, Z-corp ‘Spectrum’ and Z-corp ‘450’.

**Investigation B - From Product to Process**

This series of projects engages *Topology Optimisation* as an approach to integrating material and force-based parameters into the conceptual design process. Three studies explore three different versions of the procedure. Study one – *SpecificCity* – uses a 2D implementation named *Evolutionary Structural Optimisation (ESO)* to aid in the generation of a structural column. The intricate detailing that results from this interaction is refined in *Rhinoceros* and prompts investigation into means of fabricating highly intricate architectural scale components. Patternless casting processes used in the automotive industries are found to be the best method for achieving the desired level of detail and scale required.

Study two – *Strange Attractor* – utilises *Bi-Directional Evolutionary Structural Optimisation (BESO)*, which is a 3D implementation of topology optimisation. The version I employ is linked with a FEA package named *ABAQUS CAE™*, which is used to set up the input file and analyse the structure. The results from the BESO process are imported into *Rhinoceros* and used as a framework to design a small pavilion. Whilst *BESO3D* has since (2010) been implemented as a plugin for *Rhinoceros*, preliminary tests revealed that despite the advantage of having such a tool embedded in design-specific software, the time taken to generate analytic results remains undesirable for the conceptual design phase.

Consequently, study three – *Calibrating Generative Results* – explores a less accurate, but more rapid standalone topology optimisation tool called *TopoStruct*. Within this study I reason that physical calibration of the results from *TopoStruct* will help to address any analytic errors. Output from *TopoStruct* is imported into *Rhinoceros* for easier navigation and results are constructed using basic materials such as bamboo skewers, masking tape and foamcore. Findings from these physical models are then be fed back into subsequent design iterations.

**Investigation C – From Process to System**

Interest in further exploring optimised truss configurations leads me to a particularly fascinating family of lightweight prestressed self-stable networks known as *Tensegrity* structures. The unusual composition of these structures necessitates both material engagement through extensive physical modelling as well as exploration into ways of ‘activating’ virtual space in order to simulate and evaluate their behaviour ‘en masse’. After becoming familiar with their principles I explore a number of different 3D modelling approaches, including animation simulation using *AutoDesk 3D Max™*, a force-density plugin for *Rhinoceros* named *RhinoMembrane v1.22*, and the possibility of associative modelling. None of these approaches are found to provide the level of fluency and flexibility required for early design exploration.

Through a serendipitous series of events, I stumble upon a simple particle-spring based JAVA applet named *Struck*. Although created in 1997, it turns out to be the most suitable method I can find for digitally simulating, evaluating and testing tensegrity structures during the conceptual design phase. The integral link between form, material, structure and assembly that I outline enables fabrication using either CNC technologies or low-tech construction techniques, both of which approaches I explore.
Software Exclusions

Two popular trends in design computing are not explored in this research. Firstly, I have not extensively engaged associative modelling tools despite the fact that they are fast becoming the status quo in architectural modelling. My reasons for this are due to the fact that tools such as CATIA™, Generative Components™, Grasshopper™, Revit™, etc, do not support the explorative nature of the architectural form development process sufficiently due to the requirement for geometric dependencies to be explicitly declared from the outset. Once a fundamental geometric logic has been established, making changes to these associations is difficult. Furthermore, at present such tools do not typically support more informed decision making without significant customisation. Engaging associative tools can thus be limiting if design intent is unclear or undefined - as is often the case during early design exploration.

The second technique that was not pursued for my research but is nonetheless prevalent in contemporary design is scripting. While scripting techniques are increasingly being used by designers, my overall sense is that they are generally engaged as tools of novelty or to increase the efficiency of pre-existing processes. My focus on the intersection of computation and materialisation did not demand the use of scripting except during Investigation C, which required a set of scripts to facilitate information transfer between Rhinoceros and Struck. Having said that, if the outcomes from Investigation C are to be further developed and extended, scripting know-how, in particular knowledge of visual scripting environments such as Grasshopper and its associated plugins, will be an advantage.

1.5 Exegesis Structure

The structure of my exegesis reflects my action research methodology in that it oscillates between a critical examination of theory and a reflective account of practice. These two intersecting components inform one another and are presented in such a way as to emphasise the emergent nature of my research. Theoretical research is compiled in chapters, whereas applied research is presented as investigations.

In this chapter I have stated the problem as one centred around enhancing the relationship between design and production in architecture. I have described that my aim is to explore the extent to which computation and CNC manufacturing might allow construction insight to become an active driver during early design exploration, and whether this co-rational mode of practice could lead to new architectural possibilities and a stronger relationship between design intent and built outcome. I explained my central proposition, that digitally mediated design and manufacturing can strengthen the relationship between intention and execution by enabling closer engagement with fabrication during early design exploration, and by supporting more informed decision making via dynamic design representations with embedded material intelligence.

I then outlined my motivations and the reflective ‘action research’ methodology I have enlisted to test my hypothesis - which engages firstly with applied investigations and secondly with available literature.

In Chapter Two I identify that the contemporary disjunction between design and production in architecture is historically linked to a shift in design communication, the emergence of building specialisations and an erosion of practical knowledge among architects. I then draw on selected architectural literature to locate my research within contemporary discourse and introduce the initial question that this dissertation addresses. Namely, can direct ‘file to factory’ processes support better integrated design to production methods in architecture?
Within Investigation A I begin unravelling this question via the manufacture of small scale jewellery objects using a combination of digital modelling, additive fabrication and traditional metal casting techniques. This process reveals that a crucial aspect of utilising digital technologies for design and production is having a deep practical knowledge of tools, materials and manufacturing processes. In doing so, Investigation A thus suggests that better integration between intent and outcome may be achieved by implementing material, structural and assembly logics as parameters within digital design representations, and using their logics to actively inform and guide architectural decision-making during early design exploration.

This insight raises the question, what kinds of 3D digital modelling tools can support more informed decision making and facilitate a deeper understanding of practical construction issues and potentials during early design exploration? Chapter Three provides a context for the next phase of my applied research, which is aimed at answering this question. I identify performance based design as the contemporary paradigm associated with better informed computational design methods and elaborate on selected precedents focussed specifically on enhancing material performance in architecture. Each precedent I discuss points to new ways of informing design through an integral design to production strategy in which material, structural and fabrication logics are used to constrain early design exploration within a spectrum of rational and buildable structures and forms.

To discover the potentials and implications of using such tools for and within architectural design, Investigation B engages a generative methodology known as topology optimisation. In this series of studies I test the hypothesis that digital design representations informed by material and structural logics can better support the quest to integrate design, analysis, manufacture, and assembly in architecture. While topology optimisation on its own is found to be moderately useful, the studies reveal that linking generative digital prototypes to material exploration via simple physical modelling techniques may offer an avenue to better informed design exploration and a more coherent design to production workflow.

To build on the results of the topology optimisation research and further explore how a rapid and mutually informed digital-material feedback loop could enhance the bond between architectural design and production, Investigation C embarks on an extensive process of physical and digital prototyping. This investigation is centred around an intriguing family of prestressed trusses known as tensegrity structures. In collaboration with structural engineers, I develop and implement an integral computational design to production strategy for a new class of tensegrity. I utilise a novel interactive simulation and evaluation tool to facilitate a flexible materially informed design process. A series of design studies explores the feasibility of deploying such structures in architecture and tests the integral design to production workflow that I outline.

Within Chapter Four I summarise the results of my applied project work, suggest areas of further research and discuss the impact of approaching material, structural and assembly logics as active drivers during early design exploration. In considering how the results of my research serve to inform and transform architectural design and discourse, I elaborate on implications related to technical, cultural and philosophical aspects of architectural practice. In evaluating the research I outline how more informed and better integrated architectural design to production is specifically made possible by new interactive modes of design representation and access to rapid prototyping facilities, which together facilitate a tight link between physical and digital media during early design exploration.
2.1 Introduction
2.2 The Master Builder: A Unified Paradigm
2.3 Forces for Dis-Integration
2.4 Architecture in the Digital Age
2.5 Integration via Computation
2.6 Summary
2.1 Introduction

In today’s construction industries there is a clear division of labour between architects, engineers and builders. Although this fragmented mode of interaction and organisation has proven advantageous in many respects, in most cases it results in “a linear building process in which realisation of a project is downstream, and almost secondary to the architect’s original vision” (Ceccato 2001: 1). This sequential design, analyse, build approach has meant that architectural form “is conceived in a process that is for the most part divorced from considerations about construction” (Loukissas 2003: 32). The consequence is a significant amount of compromise and antagonism as it puts architects, engineers and builders in a reactive mode (DeSilva 2008: 1894).

The uptake of digital technologies within each of these specialisations raises questions around the fragmented and sequential nature of design and construction practices. It is widely thought that Computation and CNC manufacturing offer possible ways of addressing the disparity between design and materialisation by linking architectural conception more closely with construction through a “digital continuum from design to production” (Kolarevic 2003: 7).

To understand the factors that have led to today’s fragmented practices, this chapter first explores the historical relationship between design and production in architecture. I examine how early building practices were essentially craft-based, and how the introduction of representational conventions, the corresponding emergence of building specialisations and a gradual erosion of practical knowledge across the architecture industry catalysed a separation between ‘designers’ and ‘makers’, and contributed to the current state of affairs.

To position my applied research within the context of contemporary digital design practice and identify ways in which digital technologies might help architects address the gap between design and production, I then examine the evolution and use of computing in architecture up until the turn of the millennium.

Lastly, I review contemporary discourse around the notion of digitally integrated design to production. I describe how theorists and practitioners suggest that an engagement with digital technologies can significantly enhance the bond between intent and outcome by providing a “direct link between what can be conceived and what can be constructed” (Kolarevic 2003: 3). Since this idea is still largely an assumption among architects, it leads to my initial question; can direct ‘file to factory’ processes support better integrated design to production methods in architecture?

2.2 The Master Builder: A Unified Paradigm

The construction industry has not always functioned according to the fragmented logic that is prevalent today. Early building practices in Western Europe existed within a paradigm where the division between designers and makers had not yet been established. During this period, intention and execution were unified through a craft-based approach to production and an intimate knowledge of materials and processes of making.

The English word architect is derived from the Greek term ‘arkhitekton’; arkh meaning ‘chief’ or ‘master’ and tekton meaning ‘builder’ or ‘carpenter’. It is widely believed that up until the late Renaissance, “all of architecture could be held in the intelligence of a single maker … Part architect, part builder, part product and building engineer, and part materials scientist, the master builder integrated all the elements of architecture in a single mind, heart, and hand” (Kieran & Timberlake 2004: xi-xii).
In other words, "the person in charge [of construction] had a good understanding of engineering aspects such as the strength of material, structural stability, constructability as well as the architectural aspects such as form and aesthetic" [De Silva 2008: 1843].

During this period, a continuum existed between those who conceived buildings and those who constructed them. To reach the status of architect or master builder (also referred to as master mason or master craftsman) required many years of apprenticeship and practical experience. A master builder was expected to be familiar with both the art and science of construction, combining an extensive knowledge (episteme) of tools, techniques and materials with the technical know-how (techne) required for successful execution.

The master-builder was effectively the manager of a craft-based guild. His role was distinguished from actual craftsmen only through many years of experience and training. He was "comprehensively and intimately familiar; at the same time, with the means by which his design could be brought to realization in actual stone and mortar" [Fitchen 1961: 10]. Consequently, "structural form, strength and stability, and architectural expression were inseparable and complemented each other" [Larsen & Tyas 2003: 30].

The master builder paradigm represents a unified model of building practice in which design and construction were integrated via a culturally ingrained awareness of material logics and construction procedures. The master builder drew on a practical understanding of materials, assembly logic, structure, form and space to inform the process of translating abstract thoughts and ideas into physical constructions. This process of translation relied on heuristic methods, tacit knowledge and verbal negotiation between the master builder and craftsmen engaged in construction [Barrow 2001: np].

2.3 Forces for Dis-Integration

New Modes of Representation

Within the craft-based master-builder model of production, architectural representations were rare. According to Perez-Gomez & Pelletier, "as late as the Renaissance ... the only drawings truly 'indispensable' for building (from a technological standpoint) were Modani, or template drawings" [Perez-Gomez & Pelletier 1997: 7].

The fifteenth century witnessed a profound transformation of design and construction processes prompted by "a new mathematical and geometric rationalization of the image that radically departed from classical [Greco-Arabic] theories of vision" [Ibid: 9]. New tools for design visualisation and representation – in particular Filippo Brunelleschi’s rationalisation of one-point perspective drawing – allowed a previously inconceivable distance to unfold between the master builder and the construction process. The field of architecture which was considered part of the mechanical arts during the Middle Ages, was slowly absorbed into the liberal arts as design intent was increasingly conceived and communicated using geometric lineamenta - orthogonal and perspective projections of space, resolved on a single planimetric surface.

By the mid Renaissance, architectural projects were being commissioned and coordinated by clients who would employ and supervise a collaborative team for design and construction. "The tripartite team would include, for creativity, an artist [goldsmith, sculpture, painter] with limited knowledge of construction; for technology, a practicing architect who offered technical knowledge and on-site supervision; and for construction, a master-builder trained in the craftsman guild workshop" [Barrow 2001: np].
By the late Renaissance, the evolution of perspective representation and orthographic drawing standards allowed an architect to describe a building design remotely (Barrow 2001: np). At the same time, "the shift from direct verbal communication to indirect (visual) communications ... contributed to the growing barrier between the designer and the builder-craftsman" (Barrow 2001: np). Whilst distinguishing processes of designing from processes of making was useful with regards to enabling an expanded design repertoire and more complex built works, this separation resulted in the architect's complete withdrawal from construction processes.

The advantages of separating design from construction prompted polymath Leon Battista Alberti to argue that these interdependent aspects of building should be thought of as distinct fields. In De Re Aedificatoria, Alberti states "architecture comprises two parts, the lineamenta - deriving from the mind - and the materia - deriving from nature - mediated by the skilled craftsman" (Rykwert et al. 1988: 422-423). By distinguishing those who use their minds from those who use their hands, Alberti was instrumental in initiating "a break from the tradition of craft, whereby planning is conceived of as a separate body of knowledge and is separated from the act of making" (Shodek et al. 2005: 131). Alberti's treatise thus catalysed a belief within 'educated' sectors of society that "theory provided the essence of architecture, rather than practical technical knowledge or construction skills and experience" (Barrow 2001: np).

Mark Wigley describes how "drawing ... made it possible to elevate architecture from ... a guild practice to that of a liberal art, an art liberated from the constraints of the material world... Architecture's status as a discipline turned on its connection to paper... Paper became the real building site" (Wigley 2001: 38). In Translations from Drawing to Building and Other Essays (1988), Robin Evans describes how this has resulted in a condition whereby architects labour under a "peculiar disadvantage... never working directly with the object of their thought, always working at it through some intervening medium" (Evans 1986: 156).

Specialisation

During the nineteenth century, industrialisation brought about a vast increase in the number of materials, processes, rules and regulations surrounding building and construction. The diversification of available building products and processes meant that it was no longer possible for a single individual to maintain total control over and knowledge of the design and build process. Pressure from growing consumer markets, the emergence of new materials and increasingly complex design problems demanded that design and construction information become completely externalised so that it could be unambiguously interpreted by third party contractors (Kolarevic 2003: 57). The building and construction industries witnessed "an increase in specialisation with the emergence of various types of engineers and design consultants" (Barrow 2001: np). Territory was demarcated, categories determined and borders between 'disciplines' made clear through the implementation of strict protocols regarding collaboration and design communication.

The emergence of specialisations pertaining to, but distinct from the domain of architecture, meant that working relationships had to be defined contractually to limit the scope and liability of those involved in the building process. The flexible and interpretative representations of earlier periods were transformed into legally binding and explicit construction documentation in the form of 'contract documents' and 'blueprints' (Barrow 2001: np). Communicating design intent to various trades became a matter of producing standardised orthographic projections such as plans, sections and elevations. As a result, "traditional craft-based approaches to production gave way to process-specialization approaches... Attitudes toward not only how to make artefacts changed but also how to design them in view of the new capabilities afforded by the new production environment" (Shodek et al. 2005:17).
By the turn of the twentieth century, the typical architecture firm was both conceptually and legally severed from actual processes of construction. Architects were bound to contractual agreements that prevented them from being directly involved in building processes, sequences and procedures. The architect was situated at the top of a vertical hierarchy, coordinating a team of third party specialists and consultants who were engaged to support and facilitate their design ideas.

Generally speaking, the task of this team was to produce a set of unambiguous and legally binding two-dimensional representations that described a building in totality and could be used to construct the design from a range of largely mass-produced components. Similarly to today’s architectural practices, this set of explicit tender documents – in the form of drawings and building specifications – was distributed to a number of potential contractors who would compete for the job of construction. Once the client, architect and preferred contractor agreed upon cost and time frame, construction could proceed and the architect’s role shifted from producing and coordinating design information to merely observing the building process and ensuring that contractors complied precisely with the contract documentation.

While the fragmentation and diversification of architecture and related industries was invaluable as a means to make design more widely accessible, increase productive capacity and push outward the bounds of human knowledge, the legacy of specialisation it spawned has segregated and divided previously unified paradigms and processes. The full integration of technical drawing within design and construction processes gradually forged a clear division between architect, external consultants and builders. The practice of architecture thus became both culturally and practically cleaved from the building trades and by extension, processes of assembly and construction.

Erosion of Practical Knowledge

The explicit and legally binding nature of design representation and communication led to the evolution of a linear, adversarial, legally constrained and rigid design – build process [Barrow 2001: np]. This widely adopted linear approach has resulted in architects providing what Phillip Bernstein describes as ‘thinking’ services. He suggests that in conventional building practices, “the primary role of the architect is to think about the design and certify that thought process by virtue of his or her professional stamp on the final product... considerations of how a building is to be built - the ‘making’ - are delegated explicitly to the constructor, whose responsibilities include determining the means and methods for accomplishing the design. The architect is not to be involved in these means and methods because that is not part of the process of thinking about design. The constructor is not to be involved in the creation of design, because he or she lacks the professional standing to do so and thus arrives only after completion of the design” [Bernstein 2010: 193].

Although dividing these responsibilities has enabled the evolution of increasingly sophisticated architecture and the built expression of abstract concepts that go beyond simple utility, “the removal of the architect from the actual construction of the building introduced a discontinuity in the design-build process. This discontinuity had many benefits...[but] it also introduced problems. On one hand, the potential for miscommunication and misinterpretation of the information, and on the other, the increasing abstractness on the part of the architects’ experience” [Chastain et al 2002: 6]. Ceccato suggests that a gradual erosion of practical and material knowledge among architects has resulted in “the emancipated figure of the ‘designer’... whose work is maintained pure and detached from the mundane toils of fabrication and construction” [Ceccato 2001: 1].
2.4 Architecture in the Digital Age

The capacity to represent designs on paper prior to construction meant that it was no longer necessary for architects to concern themselves with the gritty reality of material constructions. While enabling a diverse range of new outcomes and potentials, a shift from pragmatic concerns of material assembly to the more abstract territory of ideation and visual representation – from “rough hands to smooth hands” (Kvan 2004: 83) – marked a disjunction between design conception and production. A reliance on visual means of design generation and communication in bridging this discontinuity “transformed the practice of architecture. It produced an image of practice tied to drawing” (Chastain et al 2002: 6).

The advent of digital design tools and fabrication technologies raises questions around this materially divorced design methodology and the role of the architect as providore of 2D graphical documentation. In the following section I examine the evolution and use of computing in architecture up until the turn of the millennium. The purpose is to situate and give perspective to my applied research, within the context of digital design practice and digital fabrication technologies.

Early Design Computing

Between 1962 and 1966 architects and design theorists began to identify the limitations of conventional graphically oriented design practices. In light of diversifying materials, technologies and social patterns, it became apparent that ‘intuition’ was no longer an adequate approach to building design.

In Notes on the Synthesis of Form (1964), Christopher Alexander observes, “functional problems are becoming less simple all the time. But designers rarely confess their inability to solve them. Instead, when a designer does not understand a problem clearly enough to find the order it really calls for; he falls back on some arbitrarily chosen formal order. The problem, because of its complexity, remains unsolved” (Alexander 1964: 1). He argues that “design problems are reaching insoluble levels of complexity” and discusses how “these problems have a background of needs and activities that are becoming too complex to grasp intuitively” (Alexander 1964: 3).

An inability to respond to novel and increasingly complex design challenges with conventional ‘tools of the trade’ prompted calls for an evidence-based design process. This line of thinking was formalised within the Design Methods Movement, which sought to “base the process of design [as well as the products of design] on objectivity and rationality, that is, on the values of science” (Cross 2002: np).

The development of digital design media during the 1960’s coincided with this significant shift in design theory and practice. By the 1970’s, some theorists heralded computer aided design (CAD) as a possible answer to the growing complexities faced by design practitioners. In The Automated Architect (1977), Nigel Cross argues that conventional design processes rely substantially on a designer’s experience and imagination to address functional requirements and anticipate the implications of their designs.
He points out that "in novel situations, such as designing in new materials or for new environments, experience may well be irrelevant and ... imagination inadequate" (Cross 1977). As a result, "the conventional design process seems to have a major and increasingly important shortcoming, that of failing to deal adequately with external compatibilities" (Ibid). Cross suggests that computing could enable architects to overcome dependence on pre-existing design solutions and styles by informing design through the simulation of internal and external parameters.

Despite promising research along these lines by computational design pioneers such as John Frazer and Robert Aish during the 1960’s and 1970’s, computer aided architectural design (CAAD) tools remained beyond the budget and scope of most architectural practices and institutions. By the end of the 1970’s however, both computing and the commercial CAD industry had begun to mature and were gaining significant momentum.

In 1981 IBM shipped the first Personal Computer (PC) - a low-cost alternative to the mainframe workstations that had so far dominated the design and manufacturing industries. Up to this point, CAD software was primarily developed in-house by large aerospace and automotive companies attempting to streamline manufacturing processes and automate repetitive drafting chores. A turning point occurred in November 1982 when Autodesk released the first PC-based drafting package. AutoCAD version 1 recreated the traditional drawing board environment and provided architects with a familiar and relatively inexpensive introduction to computer aided design.

Within the context of this research, it is important to understand that while significant, this first step towards digital design practices was not as ground-breaking as it seemed. AutoCAD and its relatives offer architects the possibility of increased precision and more efficient documentation processes but make little contribution to rethinking design processes or addressing complex internal and external parameters or constraints. Phillip Bernstein points out, "while the passage from analogue drawing with pencils and drafting instruments to computer-aided drafting felt momentous at the time it occurred, it was actually a mere translation of hand drawing to computerized drawing; the end results were identical, if more precise, and little change of process resulted" (Bernstein 2010: 195). As I have already mentioned, Ceccato calls early CAD systems such as AutoCAD ‘first generation’ computational design tools and similarly notes that such tools “have become gloriously infamous by not moving beyond their original paradigm: the electronic equivalent of physical tools such as pen and drawing board” (Ceccato 2001: 3).

According to pre-digital conventions, an architect is employed by a client to produce a set of unambiguous legal documentation communicating an intended building design. Engineers are engaged to ensure technical feasibility, and a builder/fabricator is responsible for constructing the design as specified. By supporting these conventions, the first generation of affordable CAD software effectively enabled industrial-era design, engineering and construction approaches to be carried forward into the digital age. Accordingly, while computers have replaced drafting tables in most architecture and engineering practices, the building industry largely maintains a fragmented and sequential collaborative logic, whereby an architect designs, an engineer analyses and a builder constructs – in that order (Nicholas 2007, White 2008).
From Static to Dynamic Representation

During the 1990s, computation and digital modelling began to significantly impact architectural thought and practice by allowing architects to move beyond the limited use of the computer as a drafting aid. This shift was catalysed by a new capacity to integrate complex 3D modelling with time-based animation processes. Animation tools were originally developed to create special effects and animations, however they presented architects with the possibility of dynamic design environments capable of simulating a variety of physical forces. Architect, educator and theorist Greg Lynn is attributed as the person who first articulated the far reaching implications of using dynamic force and time based representations for architectural design.

In response to the preceding decades of “heterogeneous, fragmented and conflicting formal systems” (Lynn 1993: 8), Lynn “made an incalculably influential move” (Ednie-Brown 2007: 15) when he articulated an alternate approach to managing the “complex, disparate, differentiated and heterogeneous cultural and formal contexts” (Lynn 1993: 8) that characterise architectural production. According to Ednie-Brown, Lynn’s “contagious move was to link technology, technique and philosophy, offering both ways of doing and modes of thinking” (Ednie-Brown 2007: 15).

In Architectural Curvilinearity: the Folded, the Supple and the Pliant (1993) 1, Lynn argues that undertaking the task of negotiating the increasingly complex architectural milieu has typically prompted two different approaches, “either conflict and contradiction or unity and reconstruction” (Lynn 1993: 8). Escewing the formal languages of Deconstructivism and Post-Modernism, he introduces ‘folding’ to describe “an alternative smoothness … that may escape these dialectically opposed strategies” (Ibid) 2.

To elucidate this nature of this alternate tactic, Lynn introduces Gottfried Leibniz’s logic of curvilinearity. He suggests that curvilinear systems can be “characterized by the involvement of outside forces in the development of form” (Lynn 1993: 9) and explains how, “the smooth spaces described by these continuous yet differentiated systems result from curvilinear sensibilities that are capable of complex deformations in response to programmatic, structural, economic, aesthetic, political and contextual influences” (Lynn 1993: 9-10). In line with Cross and the Design Methods Movement, Lynn argues that architecture should emerge as a product of the many forces and factors that need to be considered and accounted for when designing a building.

According to Lynn, introducing dynamic forces into the design process necessitates a view of the world that diverges from the reductive classical doctrine of stasis and permanence. “Architecture, in both its realization and its conception, has been understood as static, fixed, ideal and inert. Themes of motion and dynamics … are typically addressed through pictorial views of static forms. Not only have buildings been constructed as static forms, but more importantly architecture has been conceived and designed based on models of stasis and equilibrium” (Lynn 1995: np).

To explore this issue, Lynn and his contemporaries (Objectile, NOX, UN Studio, Reiser & Umemoto, R&SSie[n], Tom Kovac, Decci, KOL/MAC among others) were drawn to animation software, and began to experiment with how such tools might be used in architectural design. Lynn argues that the addition of animation tools to the design arsenal enables time, force and movement to enter architectural composition both conceptually and literally.
In animation simulations, form is not only defined by its internal parameters ... it is also effected by a mosaic of other fluctuating external, invisible forces and gradients including: gravity, wind, turbulence, magnetism and swarms of moving particles. These gradient field effects are used as abstract analogies for: pedestrian and automotive movement, environmental forces such as wind and sun, urban views and alignments, and intensities of use and occupation in time” [Lynn 1995: np]. Rather than considering architecture in explicit and stationary terms, animation tools enabled the design space to become highly plastic, flexible and mutable through motion and transformation (Lynn 1995). The “ability of these programs to stretch, fold, and distort three-dimensional forms in virtual space and to alter those forms with virtual forces such as weight and motion, made them extraordinarily powerful tools of artistic expression and exploration” [Waters 2003: 8].

Critical Reflections

Lynn’s notion of ‘folding’ expressed the desire to generate smooth and coherent mixtures from disparate elements. While this concept continues to be profoundly relevant in light of escalating social, cultural and technological diversity, the key influence it had among architects at the time was to prompt a new architectural aesthetic that has (perhaps not so) affectionately been dubbed ‘blobism’. In an interview conducted in 1998, Lynn admits that although there are many different interpretations that can be deciphered from the pivotal Folding in Architecture publication, “in the end what is understood is an aesthetic and a style that comes out of it” [Duisberg & Guinand 1998: 68].

The approach to design explored by Lynn and others during the 1990’s is characterised by fluid forms shaped by various ‘forces’ acting on and within 3D virtual geometry. "Instead of working on a parti, the designer constructs a generative system of formal production, controls its behaviour over time, and selects forms that emerge from its operation ... formal complexity is often sought out ... The designer essentially becomes an 'editor' of the morphogenetic potentiality of the designed system, where the choice of emergent forms is driven largely by the designer’s aesthetic and plastic sensibilities” [Kolarevic 2003: 42].

Although ‘folding’ architecture prompted a constructive sea change within design discourse and research, for some critics the shift towards smooth and pliant geometries suggested “a deficit of critical analysis and a superficial formalism” [Ednie-Brown 2007: 16]. Ostwald for example, observes that the outcomes from these dynamic ‘auto-generative’ design processes reveal “several qualities or characteristics that undermine any claims that the work is ethically or morally justifiable” [Ostwald 2009: 1].

The reasons behind such criticisms stem perhaps from the abstract nature of the design tools being explored and the formal exuberance of the outcomes. Whilst accounting for force is without doubt a worthwhile way of approaching architectural design, Lynn himself acknowledges that animated simulations enable virtual ‘forces’ such as occupational intensities and environmental dynamics to enter conceptual design only as abstract metaphors. As such, rather than being informed by meaningful analytic feedback, designs generated with animation tools are largely the result of subjective judgement calls on the part of architects [Ostwald 2009].
Equally worrying was that the aesthetically seductive design proposals typical of the ‘folding’ movement were visualised using imagery that—more often than not—showed little sign of materiality. Ednie-Brown observes, “the proliferation of renders in which forms floated against black backgrounds seemed to speak of an ungroundedness” (Ednie-Brown 2007: 16).

Reacting to this trend during its most pronounced stages, architectural theorist Neil Leach published an intentionally polemical book titled *The Anaesthetics of Architecture* (1999). Leach discusses how architects have over time, become increasingly obsessed with images and image making to the detriment of their discipline (Leach 1999: viii). The central argument he makes is that a preoccupation with images threatens to anaesthetise the profession from social, cultural and political concerns. Leach suggests that focusing on image production leads to a lowering of critical awareness. “What results is a culture of mindless consumption … [in which] the only effective strategy is one of seduction. Architectural design is reduced to the superficial play of empty, seductive forms, and philosophy is appropriated as an intellectual veneer to justify these forms” (Leach 1999: viii). Leach claims, “the many projects of the so-called avant-garde that fetishize the image are caught within this paradox” (Leach 1999: 78).

In Architecture and the Virtual: Towards a New Materiality (2005), Antoine Picon points out that the formal freedoms afforded by popular 3D modelling and animation tools appear to pose “a threat to one of architecture’s essential dimensions: the concrete aspects of construction and building technologies, in a word, its materiality” (Picon 2005: 114). Kenneth Frampton (1995, 2010) has also criticised computational design, noting that it “often appears to neglect the material dimension of architecture, its intimate relation with properties like weight, thrust, and resistance. On a computer screen, forms seem to float freely, without constraint other than those imparted by the program and by the designer’s imagination” (Ibid).

In response to these observations and criticisms however, Picon asks “should one accept the present stage of computer-based design as if it were setting definitive standards? As digital architecture remains in its infancy, one must be cautious not to draw conclusions about the temporary features it presents … [a] tendency towards a certain immateriality, or rather its often-glib attitude towards materiality, may very well be ephemeral” (Picon 2005: 115).

Curving Towards Materiality

Although the ‘folding’ movement raised questions around the use of computational tools in design, a positive outcome was that the manufacturing complexities raised by the curvaceous architectural geometries sparked fervent investigation into appropriate production techniques and technologies. Standard approaches to manufacturing and construction turned out to be ill suited for the geometrically complex shapes being proposed. Attempts to rationalise these designs within a reasonable budget drove early digital adopters to explore the use of advanced computational design and Computer Numerical Control (CNC) manufacturing processes originally developed for and within the nautical, automotive and aerospace industries.
These so-called non-standard approaches to production allowed design and construction information to be consolidated within a single comprehensive and data rich digital representation. By the turn of the millennium, digitally enfranchised architects were, in some cases, able to avoid using traditional technical drawings to communicate building information.

The term non-standard was formally ushered into contemporary architectural discourse via an exhibition held at Centre Pompidou in 2003 | 2004 (Figure 2.4 a). The Non-Standard Architectures (NSA) exhibition aimed to “assess the social, economic and political changes brought about by the widespread application of so-called ‘non-standard’ production processes in design, architecture and territorial and urban policies” (NSA press release 2003). The curators were interested in exploring “how the digital chain has modified … the entire economy of architectural production, from initial conception to end product” (Ibid).

Although the NSA exhibition sought to generate discourse around non-standard design to production processes, in a review of the exhibition, architectural historian Mario Carpo observes that the technical use of the term was muddied as a result of the “round, serpentine, sinuous, flaccid, floppy, and fluid forms on show” (Carpo 2005: 234). Others have also pointed out that the work featured in NSA appeared to celebrate new forms, geometries and technologies to the detriment of more culturally pressing concerns (Murray 2004: 8). Given that many of the architects who took part in the exhibition were originally affiliated with the ‘folding’ movement, it is little wonder that “alongside the technological definition of ‘non-standard’ … the Paris exhibition offered an alternative, based not on technology but on form” (Carpo 2005: 234).

Whilst for some NSA appeared to celebrate architectural ‘form’ over material ‘processes’, for others the key component in non-standard architectural thinking is “process on the ascendant over product as form” (Burry 2003: 4). According to this way of thinking, a “process-based change is far more significant than the formal change. It is (a) digitally-based convergence of representation and production that represents the most important opportunity for a profound transformation of the profession and, by extension, of the entire building industry” (Kolarevic 2003: 7).

Theoretically, the non-standard ushered in a new conceptual paradigm that, according to curator Zeynep Mennan, “ensures a never-completed space of creativity and non-identical reproduction” (Mennan 2007: 149). Practically, it marked an undeniable turning point in architectural thought and practice by broadening awareness of CNC manufacturing, new parametric modelling approaches and their combined potential for producing mass-customised architecture.

### 2.5 Integration via Computation

In the preface to the seminal book Architecture in the Digital Age: Design and Manufacturing (2003), Branko Kolarevic argues that, “one of the most profound aspects of contemporary architecture is not the rediscovery of complex curving forms, but the newfound ability to generate construction information directly from design information through the new processes and techniques of digital design and production” (Kolarevic 2003: v).
Architect and educator Scott Marble has similarly observed that, "CNC systems put the process of design closer to the production of buildings, merging production and design into a common language of digital information" [Marble 2010: 40]. Like Kolarevic he suggests that this "shift in how we communicate carries the potential ... to completely restructure the organization and hierarchy of the design and building industry" [Ibid].

It is clear both authors believe that by implementing digital design to production strategies in architecture, "the design information is the construction information" [Kolarevic 2003: 7]. Like other contemporary theorists and practitioners they assume that computation and CNC manufacturing can allow "the process of describing and constructing a design [to be] more direct and more complex because ... information can be extracted, exchanged, and utilized with far greater facility and speed" [Ibid].

The notion of synchronising design and construction information through digital tools, techniques and technologies points toward an enriched dialogue between activities of design conception and materialisation. Stern argues that "the computer has the potential to expand the professional's control over the world of built form by linking designers with constructors more closely than since the dawn of the machine production" [Stern 2010: 15]. Kolarevic takes this argument one step further by suggesting that contemporary architects are empowered through "the use of digital technology as an enabling apparatus that directly integrates conception and production in ways that are unprecedented since the medieval times of master builders" [Kolarevic 2003: 4].

Many other theorists and practitioners have similarly identified opportunities for architects to redefine their role in the AEC industries through the uptake of new digitally mediated technologies that have the potential to link design directly to fabrication and construction [Ceccato 2001, Barrow 2001, Leach et al 2004, Hensel & Menges 2004, Schodek et al 2005, Chaszar 2006, Kilian 2006, Deamer & Bernstein 2010, among a plethora of other references].

As I mentioned in Chapter One, Kolarevic provides a good distillation of contemporary thoughts and assumptions. "By integrating design, analysis, manufacture, and the assembly of buildings around digital technologies, architects, engineers and builders have an opportunity to fundamentally redefine the relationships between conception and production. The currently separate professional realms of architecture, engineering and construction can be integrated into a relatively seamless digital collaborative enterprise – a digital praxis" [Kolarevic 2006: 2-3].

Whilst in theory a seamless digital design to production process is a tantalising prospect, the question few authors raise and that I found myself stumbling into is; how might digital technologies be specifically engaged and strategically leveraged by architects in order to capitalise on their implicit potentials? Furthermore, can they really facilitate a better integrated design to production workflow?
2.6 Summary

This chapter has established some of the key factors that have led to a contemporary gap between design and production in architecture. The evolution of design representation and communication, the emergence of building specialisations, and a corresponding erosion of practical knowledge across the architecture industry have all contributed to the fragmentation of what was historically a unified construction paradigm in which the theoretical and practical knowledge required for building design and construction was embodied within one individual.

To position my applied research within the context of contemporary digital design practice and identify ways in which digital technologies might help architects address the gap between design and production, I then outlined the evolution and use of computing in architecture up until the turn of the millennium. This analysis revealed a recent shift of focus among architects towards both more informed design methods (by accounting for internal and external parameters) and an interest in rationalising complex digitally generated forms using digital fabrication processes.

Lastly, I described how it is widely assumed that an engagement with digital technologies can significantly enhance the bond between architectural intent and outcome through the synchronisation of design and building information and by facilitating a direct link from design to construction. Since this idea remains an assumption among architects, I posed the question; can direct ‘file to factory’ processes support better integrated design to production methods in architecture?

In the next chapter I describe my initial engagement with advanced computational design and manufacturing. This applied investigation is focussed on the production of small scale functional objects. It is devised as a vehicle to become familiar with a suite of digital tools, techniques and processes, as well as to test the assumption that direct ‘file to factory’ processes can support better integrated design to production methods in architecture.
A1 Introduction

In the previous chapter, I outlined a brief history of architectural design computing and described how a recent engagement with computational design tools and CNC manufacturing points to a new kind of synergy between processes of architectural design, engineering and construction. For architects, this so-called ‘file-to-factory’ approach suggests the possibility of achieving a higher degree of continuity between design intent and built outcome than is currently possible using conventional tools and industrial-era manufacturing processes.

This chapter - Investigation A: From Conception to Production - describes my initial engagement with advanced 3D modelling software and ‘file to factory’ fabrication. The main objective of this exploration is to experience first-hand the intricacies of designing and producing artefacts using digital tools and technologies. This approach is a way of unravelling the question posed at the end of the previous section - can direct ‘file to factory’ processes support better integrated design to production methods in architecture?
A2 Description

In practical terms, this investigation explores computational design, additive fabrication and ‘lost wax’ metal casting as a potential pathway to manufacturing intricately detailed wearable objects. It was initiated prior to this PhD research in late 2004 and has endured throughout the duration of my candidature. Along with the primary objective mentioned above, a secondary objective was to establish a commercially viable product to offset the costs involved with research and development.

The outcome of this investigation is a range of jewellery crafted in gold, sterling silver, and bronze. The principal collection comprises nine rings, three pendants, a set of earrings, a key ring and a pair of cuff links. The rationalisation and resolution of each of the designs was achieved through an extensive process of digital modelling, physical testing, observation, reflection and discussions with technicians, craftspeople and potential users. Through all phases, information derived from a 3D digital model was used to produce wax ‘patterns’ via additive fabrication. These patterns ultimately became ‘investments’ for prototyping and producing the finished works.

The success of this research is perhaps best illustrated by its momentum. Since production, the jewellery has appeared in a number of publications and been exhibited nationally and internationally within a variety of creative contexts.

Further to the jewellery pieces, a series of other small-scale works and collaborations are presented in this chapter, which explore alternate materials and further potentials of additive fabrication.

A3 Fabrication Approach

Additive Fabrication

While there are a myriad of potential avenues for investigation that have opened up as a result of new and emerging digital tools and technologies, perhaps one of the most straightforward in terms of directly materialising design ideas is additive fabrication. Additive fabrication is a flexible CNC manufacturing technology that supports a high degree of geometric complexity and a more or less direct translation between digital input and physical output. At present there are a wide variety of additive fabrication devices available, however relatively small working volumes restrict their application within building and construction. To date, this technology has been largely utilised in architectural design for the production of representational models.

In the last decade significant advances have been made towards implementing analogous technologies at building scale using viable construction materials. In terms of directly integrating design and construction processes, so-called freeform construction or mega scale rapid manufacturing is a very promising technology. Although this field is of great interest for architects at present it is still in its infancy.

Within the scope of this research, exploring the nexus between the virtual and physical is constrained by three main factors: cost, accessibility to fabrication technologies and the present status of research and development in the field of building scale additive fabrication. Investigation A thus focuses on manufacturing small-scale components using more readily available additive fabrication technologies.
I believe that a direct involvement with the art and science of small scale additive fabrication could provide a platform for understanding the benefits and limitations of a more or less direct translation between design and production, since the same modus operandi applies across the various scales.

Investment Casting

Previously, I had worked on a project with artist Sophie Kahn, in which a 3D wax print was used to cast an intricately detailed bronze ‘mask’ (Figure A3a [i]). This collaboration confirmed the feasibility of combining additive fabrication with traditional metal casting as a means to manufacture highly complex and relatively inexpensive metal objects. Access to a 3D Systems Thermojet wax printer catalysed an idea to undertake this research at the more manageable scale of jewellery design.

The specific process I utilised to produce the jewellery objects is known as ‘investment’ or ‘lost wax’ casting. The benefits of this technique over other casting methods is that it enables exceptionally fine details to be captured in the final metal object.

The process is relatively straightforward:

• A wax version of a desired object is attached to feeder channels (sprues) and dipped into slurry and fine sand numerous times until a sufficiently robust ceramic shell is formed
• The shell is placed upside down in an oven to ‘burn out’ the initial wax object - hence ‘lost wax’ casting
• The shell forms a mold into which molten metal is poured
• The mold is cooled down and the shell is forcibly removed. In place of the wax is a precise metal replica

A4 Design Development

Initial Studies

Working at the scale of jewellery alleviates many of the constraints typically confronted by architectural design and opens up a range of new compositional possibilities.

During my early architectural education at RMIT University, Melbourne (2003-2004), I developed a certain affinity for minimal surfaces. Minimal surfaces are curiosities that have intrigued mathematicians and designers alike. Particular characteristics that make them interesting is that they have a mean curvature of zero and are recognized for their ability to elegantly and efficiently span highly complex boundary conditions. The pioneering work of Frei Otto, Sergio Musmeci and more recently that of Ingenhoven Architects, UN Studio and Minifie van Schaik exemplify the use of these surfaces in building design and construction 5.

Figure A3a
i. Bronze lost wax casting of 3D face scan using 3D Systems Thermojet wax as initial ‘invest- ment’ (Artist: Sophie Kahn)
ii. Genome Jewellery on display as part of Yellow Brick Road @ Greenwood gallery, Melbourne, October 2007 and 2 @ Sher- man galleries, Sydney, June 2006
iii. Press and Publicity

5. Frei Otto - eg. Munich Olympic Stadium (1972)
UN Studio - Arnhem Central Transfer Hall (in progress) http://www.unstudio.com
Ingenhoven Architects - Main Station Stuttgart (in progress) http://www.ingenhoven architects.com
Although such forms remain challenging to construct at the scale of architecture, their elegance and sophistication are well suited to the smaller scale of jewellery.

Surface Evolver[^6] is a computational tool that simulates the mathematics and behaviour of minimal surfaces. It generates shapes that correlate to physical funicular formations such as tensile membranes, cable nets and pneumatic structures. I used Surface Evolver in conjunction with Rhinoceros to explore a variety of objects, approaches to form generation and surface articulation. (Figure A4a).

Whilst these early explorations fostered a promising design approach, they were hindered by their own complexity both aesthetically and practically. The need to keep costs down and justify an investment of time and money provided a framework for rethinking the entire design and production strategy.

I decided to approach this exploration as a commercial venture in an attempt to offset the costs involved. The idea of designing for a broader market than originally intended catalysed explorations into simplified forms that would appeal to a wider audience and for the purposes of economic viability could be reproduced using well established processes.

[^6]: Available online; Compiled by Professor Kenneth Brakke (Department of Mathematical Sciences, Susquehanna University).

Opposite Page:
Figure A4a
Initial design explorations
Form Generation

Exploring simple minimal surfaces enabled a more divergent design approach to unfold. After a period of experimentation, three preliminary ring designs were developed from a catenoid, a Scherk surface and a double Möbius strip.

These scaleless abstract surfaces acted as elementary diagrams from which a series of jewellery designs were derived. Combining equation driven surfaces with basic geometric deformations revealed a wealth of design potential and provided a means to generate a range of geometries that shared a coherent formal and aesthetic language. This logic was exploited to extend the three principle surfaces into a family of unique jewellery designs.

Articulation

To maximise their market appeal, the final forms are deliberately understated. As such, they do not take full advantage of the techniques and technologies being employed. To address this situation, rather than reverting to the formalism so readily achieved by digital tools, a more subtle approach was taken. From earlier experiments it was apparent that surface articulation was a suitable means of achieving the complexity required to challenge traditional modes of design and fabrication. A further process of experimentation led to a simple strategy that would satisfy both the commercial and research aims of the project.

Three distinct types of surface articulation emerged by adjusting the mesh resolution of the original surfaces. The high polygon count meshes generated through the form-finding process were regenerated as lower resolution faceted geometries. The faceted finish was further processed to generate a perforated triangular mesh frame. These three finishes – smooth, faceted and mesh – were developed to exploit the strengths of additive fabrication and metal casting as well as provide a basis for using different materials and creating differing price points.
Associative Logic

The design strategy that emerged during the initial phase of exploration engaged an underlying rule-based logic suited to associative modelling environments. In cases where topology is predetermined and geometric composition can be declared from the outset such as the jewellery presented here, associative modelling tools can accelerate and extend the process of design exploration, articulation and subsequent refinement by providing a flexible means to appraise a variety of options and accommodate fine adjustments during prototyping and testing phases.

Although this approach was not directly pursued as part of this study, to develop the entire family of fifteen jewellery pieces would theoretically require only three different parametric models (one for each of the different topologies). An approach of this kind lends itself to the notion of mass customisation whereby a limitless combination of related forms and articulations can be devised from a single model.

Cristiano Ceccato explains, “the ability to combine ... creative rule-based design systems with flexible methods of production will enable a new form of manufacturing which is freed from predefined geometric constraints ... By varying these rules, we are able to achieve a broad family of interrelated, industrially manufactured, individually unique products” (Ceccato 1999: np). Advanced use of associative modelling for jewellery design can be found in the work of US based jewellery designers Nervous System. They have produced a series of interactive applets that can be used to create custom designs that share an underlying logic.

7. See http://n-e-r-v-o-u-s.com/tools/ for further information and examples.

Branding

As the process unfolded I was prompted to think more seriously about the commercial prospects of this investigation. A series of discussions with peers and colleagues lead to the birth of the brand ‘Genome’, which is one of my nicknames and also a rather fitting metaphor. I created a striking logo that could be used as branding device and makers mark.

Although the process of adding the logo to the final pieces was relatively straightforward, a number of opportunities presented themselves through unexpected glitches in the software I was using. In one instance, a mesh surface spontaneously ruptured during a Boolean operation. This unexplained deformation became the basis of a particularly eye-catching surface articulation. In a further instance, a similar operation caused a number of perforations to be mysteriously filled in. Again this unintended surface effect was retained. Whilst working well at the scale of industrial design, such unexpected occurrences may be more difficult to assimilate into the less flexible processes of architectural design and construction.

Figure A4d
A selection of images to illustrate branding concept and implementation.
A5 Prototyping

Surface To Substance

To begin the physical prototyping process, it was necessary to give some substance to the zero thickness surfaces that had been developed during the design phase (Burry 2003). Without any direct and formal experience in gold and silver smithing to draw from, it was difficult to determine the best negotiation of strength, weight and feel for the various designs.

Early discussions with a local jewellery manufacturer helped to ascertain and integrate some of the disciplinary knowledge that was missing. This interaction was significantly aided through an ability to visualise the proposed pieces on a laptop during meetings with the casting technician. Through the dialogue that developed, it became clear that the geometries I proposed were feasible to cast provided they could be produced as three dimensional wax objects with a minimum wall thickness of 0.6mm.

These discussions helped to establish a practical framework for materialising the designs and brought to attention important considerations such as fabrication tolerances, material shrinkage and placement of casting ‘sprues’. This information was instrumental to guide preliminary rationalisation of the zero thickness surfaces.

Wax Prototyping

Initial prototyping was carried out using a 3D Systems Thermojet wax printer located at the Spatial Information Architecture Laboratory (SIAL), Royal Melbourne Institute of Technology (RMIT). At the time, I was employed to run the digital fabrication facilities within the SIAL modelling workshop and thus had complete control over the 3D printing process from the submission of fabrication information to the extraction and post-processing of the prototypes.

The initial prototyping was invaluable for adjusting functional aspects of the shapes such as fit and verifying castability with the manufacturer. This was particularly important for the rings, whose geometries were fine-tuned to enhance their feel. The process of shape refinement was iterative and each prototype was tested on a variety of potential users until there was a general consensus that the final products were comfortable. The results are perhaps most pronounced in the popular Loop rings, which often surprise clients as they look unusual but are generally found to be surprisingly comfortable.

Prior to initiating the first prototyping phase, I envisaged that the sacrificial wax patterns needed for the lost wax casting process could be produced with the Thermojet printer. When I extracted the initial prints, it became apparent that this particular technology was not capable of producing the consistent surface finish that I desired. Primarily this lack of suitability was due to the difficulty of effectively removing the support material from the delicate jewellery pieces.

To pursue this research further, it became necessary to find a high-resolution 3D printing technology that utilised a support material that could produce an even surface finish and be easily removed without impacting the precision of the final jewellery pieces. A broad investigation into various solid free form fabrication technologies revealed a decisive shift within the industry away from representational models, towards processes that can facilitate both the direct and indirect manufacture of end-use parts. The jewellery industry has been one of the first to adopt this approach due to its agreeable scale, and a number of proprietary systems are on the market that can produce wax-like patterns that are suitable for the investment casting process.
The most appropriate technology I found was an exceptionally high precision printer developed by Solidscape Inc. The Solidscape t66 and t612 are targeted towards the jewellery and medical instrument manufacturing industries. They can deposit layers of material as fine as 0.013mm and are capable of achieving features as small as 0.25mm. The build material is a relatively brittle wax-like substance specifically engineered for the investment casting process. Importantly, the process uses a secondary support material that dissolves in a kerosene bath, leaving an even surface finish all-round.

A company with the Solidscape technology was located in Queensland. A dialogue was initiated and they agreed to do a test print of one piece. I emailed my most intricately detailed design to test the printing resolution and the surface finish. I received the wax pattern in the post a few days later. It was of exceptionally high quality and captured every minute detail of the intended design.

Metal Prototyping

The local jewellery manufacturer who had been instrumental throughout the design process agreed to attempt casting the initial Solidscape wax print while tactfully avoiding any responsibility should it fail. I delivered the pattern to the workshop and picked up the cast silver replica the following day. It was perfectly formed in sterling silver and captured every minute detail of the original wax piece. This exciting breakthrough functioned as a critical proof of concept demonstrating the feasibility of the design and manufacturing process. It also revealed the incredible level of detail that could be achieved. The sterling silver prototype can be seen in figure 5. It has hundreds of triangular perforations with edges of less than 1mm.
Feedback from the cast metal prototype was used to further refine and enhance the final pieces. Three particular observations and corresponding adjustments were made:

- Firstly, the perforations were too small – at a distance of more than 50cm the detail was imperceptible to the human eye. This observation led to increasing the size of perforations such that the complexity of the mesh pieces can be seen from a greater distance.

- The second observation came from a jeweller who raised awareness of the topographical contours that were visible on the metal surface. I had noticed similar textures on earlier wax prototypes and quickly recognised them as artefacts from the layer-by-layer build process. This unexpected and striking effect is exaggerated in the final cast pieces by ensuring correct orientation of the pieces and requesting a coarse layer thickness.

- A third observation was made after removing the sprue channels and polishing the piece. The sprues were positioned along the edges of the piece so as to minimise any interference with the primary surface. In my original design, the edges had not been given any ‘bleed’ to allow for sprue removal. In the prototype, unattractive triangular cross-sections can be seen to interrupt the smooth edges. To account for the finishing process, the final perforated forms have a metal rim at least 0.3mm thick. This thickening allows sprues to be removed and the edges sanded and polished without affecting their intended smoothness.

The process of refinement continued for a few months, during which numerous iterations of the various pieces were produced. This gradual evolution enabled competing constraints such as the thickness, strength and weight of the pieces to be negotiated with cost and appearance.

During this process I discovered the hard way that the density of gold is almost double that of silver. The first gold pieces I produced ended up close to double the cost I had originally budgeted. Not only did they prove too expensive to be economically viable, but the extra density negatively impacted the feel of the pieces by making them top heavy. As a result, instead of the 1mm thickness used for the silver pieces, the designs produced in gold were regenerated with a thickness of 0.7mm to decrease the amount of material needed and increase their comfort.

A6 Production

Final Production

During the final stages of prototyping, I began to explore how I could reproduce the complex jewellery forms without the repeated expense of 3D printing. To create a mold for a piece of jewellery, a ‘master’ pattern must be embedded within rubber or silicone. Once cured, the block of material is cut open and the ‘master’ released. When the pieces of the mold are reassembled, a cavity is formed into which inexpensive wax can be injected and released between 25-50 times before the mold becomes useless.

Initial tests revealed a number of important considerations:

- Firstly, shrinkage occurs both during production of the inexpensive wax pattern and within the casting process, thus a finished object created from a mold is perceptibly smaller than the so-called ‘master’. To account for this, it is necessary to adjust the size of the originals. I found 2.5 percent to be an acceptable allowance.
Secondly, silicon molds capture a higher level of detail and undergo less shrinkage, although rubber molds have a longer lifespan. In some cases using silicone proved necessary in order to pick up minute details that the rubber could not achieve.

Thirdly, the seams of the mold are visible on the final pieces. It is therefore important to specify to the mold-maker a preferred location for the seams and make note of the features that should not be disturbed.

Lastly, the molding and casting process requires channels or ‘sprues’ through which molten wax and metal can flow into the piece. The position of sprues is another important factor in determining the appearance of the outcome. To avoid disfiguring or destroying significant features, a preferred position should be specified at each stage of the process.

The final jewellery collection targets two price points. All smooth and faceted finishes are produced in sterling silver (key ring also in bronze) from either rubber or silicon molds. This allows inexpensive reproduction of the wax investments and enables competitive retail pricing. In contrast, the mesh pieces are formed directly using a 3D printed wax pattern in 9ct and 18ct gold. Obviously, the cost of this material means these pieces appeal to a different set of clientele.

Finishing

An important consideration and site of exploration was the finishing process. The cast pieces exhibited an unexpected whitish lustre when released from their clay investment. Originally I had envisaged the designs with a mirror finish, however early tests revealed the time consuming nature and incredible difficulty of attaining such a finish by hand. Furthermore, the combination of curvilinear forms and the additive layering process had produced unexpected surface effects that enriched the textural quality of the complex geometries. After a few rounds of further experimentation, to save time and for aesthetic purposes, I chose not to touch the primary surfaces, instead contrasting their white lustre and unexpected topographical texture with mirror finish edges.

What was interesting about this part of the process was that it required familiarisation with the various strengths and resistances of different metals – in this case silver, gold and bronze. Furthermore, I was forced to develop a personalised approach to cleaning and polishing the pieces. Learning the feel of each of the different metals and finding the right tools for each stage of the finishing process was an iterative procedure that took place over a few months. It is in many ways ironic that despite the automation, sophistication and precision of the design and manufacturing tools I employed, producing the final pieces still requires numerous manual processes. Though somewhat repetitive, in my opinion the manual nature of these tasks further serves to infuse a certain vitality into the final objects.
A7 Further Examples

Three further studies have been developed using a similar design and production logic to the jewellery. However, where the jewellery pieces presented thus far use 3D wax printing as a basis for indirect manufacturing, these projects employ more robust materials that enable direct manufacturing. In other words, the 3D print becomes the final object with little further processing.

Children Don’t be a Burden on Your Parents

The first example is a collaboration with Melbourne based artist Darren Sylvester who approached me to assist in the production of a sculpture that was exhibited at the Australian Centre for Contemporary Arts (ACCA) in 2006 as part of an exhibition titled NEW06. The piece was called Children Don’t be a Burden on Your Parents and was a three dimensional version of the Nestle company logo measuring approximately 700 x 350 x 150 mm. Sylvester had attempted to hand sculpt the piece in clay, however was not happy with the results as he desired a smooth plastic finish which was difficult to achieve manually. To overcome this difficulty, I interpreted the logo and modelled the 3D version using Rhinoceros. A watertight stereolithography (.stl) file was produced and sent to the artist. The final exhibition piece was 3D printed in ABS plastic, sanded smooth and polished.

8. NEW06 was held from 14 March - 14 May 2006
Coloured Plaster Jewellery

The second is a continuation of the jewellery investigations. I was invited to participate in a group fashion design exhibition held at Greenwood Gallery in South Melbourne during October 2007. The exhibition was titled *Yellow Brick Road* and themed accordingly. I was asked to produce a range of suitable jewellery pieces. Due to time constraints, rather than producing new geometries, I chose to explore the possibility of using a Z-corp Spectrum colour 3D printer to produce the final works. I aimed to map recognisable images from the Wizard of Oz onto the surfaces of the existing pieces. Preliminary tests revealed that this was indeed a viable idea and that infiltrating the brittle 3D plaster print with Z-corp’s proprietary curing agent (Zbond 101) provides enough strength to be wearable. The final pieces are sanded smooth and lacquered for feel and durability.

This same approach has been used more recently in collaboration with Melbourne based artist Victor Holder to produce a series of bracelets and objets d’art mapped with his visual artworks. These pieces utilise a fairly new 3D colour printer (Zcorp 450) that enables higher definition printing in more vivid and vibrant colours than the Z-corp Spectrum.
Reading Lantern

The final investigation is a reading lantern produced as a gift. Once again I wanted to use a Z-corp Spectrum to directly manufacture the finished piece. Besides the act of kindness, my motivation was to investigate more sophisticated modelling techniques and fabricate a lighting object that could not be produced in any other way. Having noted the translucent nature of the thin plaster jewellery pieces, I wanted to explore the idea of creating a lamp that would alter its appearance once the light was switched on. Within the final mushroom shaped object this effect was achieved by creating polygonal indents on the inside of the ‘cap’ and ‘stem’ elements. When the light is switched on, the narrower parts of the skin allow a soft light to penetrate, illuminating the polygonal frame on the interior of the lamp. The lamp is constructed using three individually printed pieces of water cured Z-corp composite powder (ZP 140). A halogen globe is mounted in its base and shines upward through the stem to illuminate the ‘cap’. The Z-corp plaster material turned out to be a good choice as it is unaffected by the extreme heat generated by the halogen globe.
A8 Findings

Rapid Prototyping vs Rapid Representation

Investigation A principally demonstrates how computational design, additive fabrication and traditional metal casting can be combined to manufacture intricately detailed small-scale objects.

My approach to using additive fabrication differs significantly from how it is commonly used as a tool for architectural design. More often than not, in architecture additive fabrication, a so-called rapid prototyping technology, is not used for prototyping but for what might instead be called rapid representation.

In a publication addressing the role of models and model-making in architectural design, Rory Hyde compares the process of making a pleated cardboard model to a 3D ‘physical facsimile’ of the same model produced via additive fabrication. He observes, “in many ways [the 3D print] was the least valuable of all the models produced. The translation between digital and physical is almost too seamless, there is no hands-on intervention, so that no accuracy is lost, but equally no understanding is gained” [Hyde 2008: 147].

Hyde’s observation contrasts with my own experiences due to the fact that my approach expressly used 3D printing for prototyping and manufacturing rather than representation. I found my initial 3D wax prints to be exceptionally helpful tools for both aesthetic evaluation and refining the comfort and feel of the jewellery designs. Rather than engaging additive fabrication as a tool for aesthetic evaluation only, approaching it as a tool for prototyping and/or manufacturing enables meaningful feedback about materialisation to inform and guide further design exploration.

Rapid Digital-Material Feedback

The quality of the resulting jewellery pieces is largely due to rapid feedback loops that were able to develop between concept and object throughout the process. Working at the scale of jewellery allowed for rapid design and production iterations, which is an important mechanism for uncovering the complexities and limitations around utilising and implementing advanced design and production technologies.

A further factor for success was the close relationship that was developed with a local manufacturer at the formative stages. This alliance enabled practical advice and experience-based knowledge to inform design from the outset.

Direct access to prototyping equipment and close physical proximity to the manufacturing premises further accelerated design development through the rapid feedback that could be gained through fast turnaround times and face-to-face discussions with casting technicians. These discussions were of particular benefit due to the difficulty of representing the non-conventional jewellery forms in two dimensions.

This investigation illustrates that a high level of integration between design intent and materialisation is made possible through the use of digital technologies. Importantly however, this capacity hinges on an ability to rapidly cycle through and obtain feedback from numerous iterations and translations across multiple medias and materials.
Digital | Material Fluency

Although the outcomes I have produced during this investigation are not buildings, they serve to illustrate a new kind of synergy between design and production made possible through computational design and CNC fabrication. It is crucial to note however, while digital tools and technologies make it possible to achieve higher levels of integration between processes of designing and making, my experiences suggest that leveraging their full potential requires fluency in relevant digital software complimented by an intimate practical (hands-on) knowledge of materials and manufacturing processes.

Throughout this investigation my evolving knowledge and intimacy with the limits and affordances of digital modelling, additive fabrication and investment casting began to guide my design thinking and process. Instead of focusing on idealised jewellery forms, my approach evolved to become one of co-rationalisation, whereby material, economic and fabrication concerns began to actively guide the form generation and articulation process. Rather than being implemented as a design ‘vision’ with a predefined form, design intent became something of a general trajectory - influenced and guided by the various parameters relating to the potentials and constraints of production.

In other words, fluency in relevant software and intimate knowledge of key fabrication considerations enabled the logic of materials and logistics of materialisation to actively guide and inform early design exploration and subsequent design refinement.

A9 Summary

Investigation A tested the notion that computational design tools and CNC manufacturing could bring about better integration between processes of design and fabrication. By engaging directly with digital technologies towards the production of commercial design objects, it has been possible for me to begin to understand and reflect on some of the implications and potentials of these new tools.

The applied research presented in this chapter demonstrated that computational design and additive fabrication can be successfully used to directly and/or indirectly manufacture small scale functional objects. I found that having direct control over fabrication information substantiates Scott Marbles assertion that “CNC systems put the process of design closer to ... production ... [by] merging production and design into a common language of digital information” [Marble 2010: 40]. This synchronisation of design and construction information seems to suggest that digital technologies might allow architects to achieve a greater sense of control over built form.

Investigation A revealed that while computation and CNC manufacturing may provide architects with a platform to work more directly with fabrication information and processes, achieving more control and better integration between design and production relies substantially on a direct and intimate involvement with materials and manufacturing.

The results of this investigation suggest that considering fabrication during early design exploration could help architects gain further control over design outcomes and achieve even better integrated production processes.
Figure A9a
My artistic impression of projected mega-scale rapid manufacturing potentials based on jewellery explorations (2006)
CHAPTER THREE

3.1 Introduction
3.2 Towards Informed Design Computing
3.3 Precursors, Parallel Research and Precedents
3.4 Summary
3.1 Introduction

In Chapter Two I described how the contemporary gap between design and production in architecture is historically linked to modes of design representation and a gradual erosion of practical knowledge in the architecture industry. I then outlined the evolution and use of digital tools in architecture up until the turn of the millennium and discussed widely held assumptions regarding the implications of so-called ‘non-standard’ design and production processes. The general hypothesis offered by theorists and practitioners is that computation and CNC manufacturing can support more informed and better integrated architectural design to production methods.

Investigation A tested this proposition through applied research and revealed that achieving more control and better integration between design and production is not as straightforward as it might at first appear. While computation and CNC manufacturing provide architects with a platform to work more directly with fabrication information, I found that this endeavour relies substantially on a direct and immediate involvement with materials and manufacturing processes. This finding suggests that although digital tools and technologies are a key part of the equation, considering materials and fabrication at the earliest possible stage may be the lynchpin around which enhanced control over design outcomes and expanded production capabilities revolve.

It follows that the goal to integrate “design, analysis, manufacture, and the assembly of buildings around digital technologies” [Kolarevic 2006: 2-3] could potentially be better supported if material, structural and assembly logics are used to actively inform early design exploration. Since conventional design software is not yet capable of facilitating such an approach, what kinds of computational tools can architects look towards to support this effort?

The quest to identify and develop digital tools that facilitate more informed design decision making is not new. In this chapter I describe performance based design as the paradigm associated with better informed computational design methods. I then analyse specific precedents that point to new ways of guiding the conceptual design phase through materially informed digital design to production processes. This literature and the precedent studies that follow provide a context for the next phase of my applied research and serve to further my understanding of how materially informed computing might be implemented to enhance architectural design outcomes.

3.2 Towards Informed Design Computing

Performance Based Design

Over the last decade, architects and engineers have been actively exploring how computation might enable engineering based evaluation to inform conceptual phases of the architectural design process, so that information “typically developed downstream and only acted upon reactively [is made] available to help actively guide early design exploration” [Nicholas 2008: 17]. Informing conceptual design through evaluative feedback from engineering has come to be commonly known as performance based design - defined broadly as an “approach to architecture in which building performance is a guiding design principle” [Kolarevic 2005: 3]. The premise underlying performative approaches is that feedback from computational simulation and analysis are used to inform and guide early design exploration and subsequent design development. Performance based design is thus “a method for shared and creative problem solving which makes use of new 3D digital modelling and analytic tools and a generative approach to architect engineer design exploration and synthesis” [Nicholas 2008: 105].
From a technical point of view the concept of building performance focuses on quantifiable factors such as structural and material feasibility, space usage, thermal flows, lighting, acoustics, fabrication and assembly (Shea 2004, Kolarevic 2005, Leach 2008, Nicholas 2008). As such, performance based design can be regarded as a design approach that begins to address the issues raised by practitioners, researchers and theorists during the 1960’s by providing a platform to better inform design through the simulation of internal and external forces and parameters.

This approach expands the paradigm initially identified by theorists such as Nigel Cross and partially actualised by Greg Lynn and his contemporaries using key-frame animation software. Significantly, rather than being ‘driven largely by the designer’s aesthetic and plastic sensibilities’, performance based design enables architectural decision making to be based on an analysis of design possibilities against stringent compatibility and feasibility criteria. Aesthetics still play an important role in the decision making process, but is not the foremost concern.

Put simply, with performance based design strategies, “structural, constructional, economic, environmental and other parameters – concerns that were once relegated to the realm of secondary concerns ... become primary, and are being embraced as positive inputs into the design process from the outset” (Leach 2008).

Current Limitations

While the idea that computational simulation and analysis can inform early design exploration seems reasonable in theory, at present there are at least two considerable obstacles in practice. Firstly, “most of the commercially available building performance simulation software, whether for structural, lighting, acoustical, thermal or air-flow analysis, requires high-resolution, ie. detailed modelling” (Kolarevic 2005: 198).

Secondly, “there is currently an abundance of digital analytic tools that can help designers assess certain performative aspects of their projects ... after an initial design is developed, but none of them provide dynamic generative capabilities that could open up new territories for conceptual exploration in architectural design” (Ibid: 200).

The loosely defined and explorative nature of conceptual design, as well as the time required to obtain, evaluate and implement changes based on results from ‘high resolution’ modelling and analysis, make such tools inappropriate for early design exploration in architecture (Kolarevic & Malkawi 2005). Effectively, this means that while building performance has become a popular topic in architectural research and discourse, it is actually rarely used to drive conceptual design development in practice (Kolarevic 2005: 196). Kolarevic suggests that “a certain degree of representational integration across a range of ‘low-resolution’ performance simulation tools is a necessary step for their more effective use in conceptual design” (Ibid). Moreover, “the performance assessment has to be generative, not only evaluative” (Ibid). In other words, to be useful within early design exploration, performance based design tools should not only support loosely defined parameters and provide quicker feedback, they should also assist in the generation of alternate design configurations that may increase specific building performance levels.

In theory, design tools allowing for an integral analysis - synthesis loop are an appealing and powerful way of conceiving architecture. In practice however, ‘activating’ design environments according to performance-based logics is not an easy task. Kolarevic notes, “the challenges of developing such software ... are far from trivial” (Ibid) as they require architects and engineers to fundamentally rethink how conventional building performance simulation might interface with conceptual design tools. Achieving a satisfactory level of integration between these two distinct computational paradigms appears to necessitate a fundamental shift away from considering computation for analysis or synthesis only, to thinking about it in terms of supporting both analysis and synthesis (Malkawi 2005: 87).
3.3 Precursors, Parallel Research and Precedents

Precursors and Parallel Research

Despite the challenges involved in implementing generative performance based design strategies in architecture, there are a number of practical examples that act as precursors and sites of parallel research.

A significant departure point is the research carried out by John Frazer et al. at the Architectural Association (AA) and published in the seminal text *Evolutionary Architecture* (1995). Here, Frazer likens architecture to a complex system of energetic transactions and interactions. Through applied computational research, he explores the notion of embedding design logic within a digital ‘seed’ and allowing its virtual ‘growth’ to respond to a variety of simulated environmental forces. Although Frazer’s theories remain an important contribution to architectural discourse, his practical work was limited at the time by a number of technical factors.

More recent research carried out within the Emergent Technologies (EmTech) cluster at the AA has sought to extend Frazer’s practical and theoretical investigations. Making use of sophisticated parametric modelling and engineering analysis software, this work has aimed to identify and explore so-called ‘biomimetric’ and ‘morphogenetic’ design methodologies, whereby architectural form is developed in response to functional criteria and environmental factors such as heat, light, wind and rain (Hensel & Menges 2006).

Concurrently, a number of more technical engineering-led studies have demonstrated how lighting and/or thermal analysis might be used generatively for architectural design and optimisation. Caldas and Norford (2002) report on the use of genetic algorithms to optimize the size of windows for lighting, heating and cooling performance.

Luebkeman and Shea (2005) describe a method for building envelope optimisation that accounts for internal daylight conditions, thermal performance and overall cost. Nicholas (2008) negotiates optimal daylight conditions and floor area within a medium rise tower by automating the perforation of floor slabs according to feedback from lighting analysis.

Selected Precedents

At the start of this chapter I suggested that integrating design, analysis, manufacture, and the assembly of buildings around digital technologies may be better supported if material, structural and assembly logics are used to actively guide and inform early design exploration. Considering this hypothesis, the following precedents relate particularly to computational design approaches that implement material, structural and assembly logics as parameters with which to drive, appraise and execute architectural design. They are discussed as a way of more specifically contextualising and informing the next phase of my applied research.

**eifForm**

*eifForm* is a generative design and optimisation tool developed by Kristina Shea at the Engineering Design Centre, Cambridge (Shea 2004: 101). It operates quite differently from usual structural analysis software in that it generates an optimally directed structural solution, rather than simply analysing a design that has already been proposed (Leuppi & Shea 2008: 28). *eifForm* implements a design search method called structural topology and shape annealing (STSA) (Shea & Gourtovaia 2004).
STSA combines structural grammars, performance metrics, structural analysis, and stochastic optimization to integrate goals of efficiency, economy, utility, and elegance (Shea & Cagan 1997). eifForm is remarkable in this sense as it helps to negotiate multiple competing goals and agendas.

Utilising eifForm for design generation requires creating a starting point that reflects intent through a model of the design conditions (Shea 2004: 95). This takes the form of an initial structural layout including points of support and loading along with other design and performance constraints. Design development is informed via a process of optimisation towards specified performance criteria. The output consists of triangulated, stable and buildable single layer truss forms that incorporate structural framing details as well as joint assembly specifications.

*eifForm works by repeatedly modifying an initial design with the aim of improving a predefined measure of performance, which can take into account many different factors, such as structural efficiency, economy of materials, member uniformity and even aesthetics, while at the same time attempting to satisfy structural feasibility constraints*” (Shea 2004: 93). While the process itself is largely automated, it is clear from constructed projects that the evaluation of fitness between iterations, as well as modifications to structural layout relies substantially on designer intervention.

In *Directed Randomness* (2004) Shea describes the design and construction of the first 1:1 prototype of a structure generated using eifForm. The project was a collaboration between three architects (Neil Leach, Spela Videcnik & Jeroen van Mechelen), with Shea acting as engineer and operator of eifForm. The *Hylomorphic Project* [2006] is another built work generated using eifForm. It was constructed for the GenHome Project exhibition at the MAK Centre for Art and Architecture in Los Angeles. It was a collaboration between Open Source Architects (OSA) and Arup (Leuppi & Shea 2008).

A comparison of these projects raises some interesting issues to do with generative design and optimisation tools. Despite the fact that the locations of these two schemes are miles apart and that different architects were involved, the two projects are surprisingly similar in many respects. While interesting and innovative in their own right, the built outcomes share a certain generic aesthetic quality informed partly by limitations with the specific implementation of eifForm deployed, and partly as a result of how it was used and by whom.

The similarities relate firstly to eifForm’s use of a generic triangulation schema. Shea notes that for eifForm to be a more effective architectural design tool, “further structural classes need to be developed” (Shea 2004:100). Secondly, while intended as a conceptual design tool for architects, in both projects eifForm was operated by an engineer. Instead of being directly involved in the formulation of input conditions, “the architect generally took on a new role of interpreting and analysing forms rather than explicitly creating and manipulating geometry” (Ibid: 95). This kind of distanced interaction between designer and design tool means that conceptual design iterations are not as rapid (and therefore extensive) as they could otherwise be.

Figure 3.3b
The Hylomorphic Project: Installation at Schindler House, Los Angeles 2006; digital model; physical scale model and computational form finding.
[Image Source: OSA proposal 2006]

In *Approaches to Interdependency: early design exploration across architectural and engineering domains* (2008), Paul Nicholas reports on a series of projects undertaken during his PhD internship at Ove Arup & Partners in Melbourne, Australia. In a section titled *Design | Analysis* (167-200), Nicholas demonstrates how tools typically used by engineers to analyse preexisting designs, could be used “actively and generatively [by architects] to guide and synthesise design exploration” (Nicholas 2008: 132).
The section describes three projects that explore various ways of developing generative feedback loops between ‘high-resolution’ analysis software (Radiance, Ecotect, Oasys GSA) and commercial design software (Rhino, Generative Components).

Two of these projects explore how lighting analysis could be used to drive aspects of design exploration. The first project – Venice Bridge – “addresses the generation of optimally sized and located window openings in a facade” [Nicholas 2008: 169-170]. The second – Cheese Tower – “determines the most efficient configuration of light-wells and floor space for a given building mass to allow the highest average daylight factor, evenly distributed, within that building” [Nicholas 2008: 181-182].

While these two projects demonstrate innovative implementations of performance-based design strategies, the third project – SkyBridge – is more aligned with the theme and intent of my research as it “explores the use of structural analysis as a means to find form, or to suggest possibilities” [Nicholas 2008: 195].

SkyBridge is a speculative design for a footbridge connecting two buildings over an alley. The procedure Nicholas executed is as follows:

- A rhinoscript is used to fill the space of the alley with 100 randomly positioned points, after which each point is connected to its nearest five points.
- Point entities representing loads (human traffic) and restraints (structural supports on nearby walls) are added.
- The resulting network of points and lines is analysed using Oasys GSA, which returns displacement values for each node. The nodes with the lowest displacement are moved towards those with the highest.
- Superimposed nodes are deleted and corresponding member sizes increased.
- The process is repeated until a specified percentage of the original elements are removed. What remains is a framework that represents the optimal truss configuration for a given set of loading and boundary conditions.

Although SkyBridge is simple in scope and has certain limitations, it successfully demonstrates the potential of using structural analysis to actively guide the design process. Nicholas concludes, “the project led to an enlarged solution-space for the designer, informed by structural analysis, which could be explored at speed and with relative ease” [Nicholas 2008: 196].

CADenary tool v2

A somewhat more tactile generative design and optimisation tool is CADenary tool v2, a ‘hanging chain’ simulator developed by Axel Kilian in 2004. It extends an earlier 2D implementation called CatenaryCAD developed by Dan Chak, Megan Galbraith and Axel Kilian for a computer graphics course in 2002 [Chak et al 2002].

The motivation behind CADenary is to provide a computationally enhanced version of Gaudi’s atelier [Chak et al 2002: 3]. The benefits being that “computer-aided catenary designs will be quicker and provide room for playing, trial and error, and potentially provide a means to create more complex designs than imagined in the physical world” [ibid: 5].

CADenary is based on particle-spring systems, widely used in computer science for creating realistic physical simulations for animating clothing and other fabrics [Kilian & Ochsendorf 2005].
While exploiting animation-based processes, a feature that distinguishes CADenary from typical key-frame animation processes is that it is continuously solving, "which allows the user to interact with the simulation while it is running" (Kilian & Ochsendorf 2005: 1). A Java based version of CADenary is freely available online, while a faster, more robust version that handles larger particle spring networks has been implemented in C++ for research purposes (Kilian 2005: 14).

In Particle-Spring Systems For Structural Form Finding (2005), Kilian & Ochsendorf introduce CADenary as a three-dimensional design and analysis tool for finding structural forms based on the ‘hanging’ chain method. They provide several technical examples and early design examples that demonstrate the procedure in both two and three dimensions. Linking Hanging Chain Models to Fabrication (2005) explores how fabrication schemas for physical mockups of the digital hanging chain can be linked to real time form finding simulation. While providing a compelling early example of what could be described as a ‘third generation’ modelling environment, both articles acknowledge that a significant amount of work is required before particle-spring based modelling becomes a practical design methodology.

What makes CADenary unique from the point of view of integrating analysis and synthesis, is that "the user can change form and forces in real time while the solution is still emerging" (Kilian & Ochsendorf 2005: 1). Interacting with a live, force-geometry linked structure "allows for real-time discovery of structural form rather than analysis or optimization of an existing form" (Kilian & Ochsendorf 2005: 7). Furthermore, by allowing designers to interact with a structural form and rapidly experiment with alternative solutions, "particle-spring systems can help to introduce structural evaluation environments into an architectural design process as early as possible" (ibid: 6).

Kilian suggests that introducing interactive form finding tools such as CADenary during the early design phase could allow architects to cultivate an intuitive understanding of structural behaviour when exploring complex forms (Kilian 2005, Kilian & Ochsendorf 2005).

Timber Textiles

A more direct involvement with material, structural and assembly logics can be seen in research currently being carried out both at IBOIS: Timber Construction Laboratory at École Polytechnique Fédérale de Lausanne (EPFL), and the Institute for Computational Design (ICD) at Universität Stuttgart.

Researchers at IBOIS have explored the design, analysis and construction of timber rib shells using in-house software called GEOS (Geodesic Line Modeler), developed to calculate grids of geodesic lines on free-form surfaces [Pirazzi 2006]. GEOS enables the manipulation of Bézier surface control points, the designation of start/end points for geodesic lines and the definition of connective logic between timber lathes. The system is examined via the construction and testing of a timber rib shell prototype. It is reported, “precision of the calculated geodesic lines, of the computer controlled prefabrication of the lathes and its assembly was found to be highly satisfactory” [Pirazzi 2006: np]. GEOS provides a compelling example of a materially aware computational design approach. It implements a remarkable design methodology that combines a ‘top-down’ visual manipulation of surfaces with a ‘bottom-up’ materially driven approach to fabrication and assembly.

More recently, IBOIS have been focussing on “a new family of timber constructions based on principles of origami folded plate structures and textile fabrics” [Weinand 2009: 111]. What makes this work particularly pertinent is firstly that material properties are “considered as an active parameter of the design process” [Weinand 2010: 104]. Secondly, rather than simply proposing new methods for timber construction, 1:1 scale prototyping is used to test the mechanical and structural behaviour of these systems. The aim of this work is to develop calculation methods capable of determining the structural stability of highly complex timber constructs [Weinand 2009: 118]. While physical models play a key role in this process, it is acknowledged that digital tools are “indispensable for exploring the potential of the discovered phenomena” (ibid: 117).
Researchers at ICD have similarly been exploring timber construction focused particularly on potential intersections between computation and materialisation. Their approach seeks to develop and employ computational techniques and digital fabrication technologies that extend the concept of material systems by “embedding ... material behaviour; geometric characteristics, manufacturing constraints and assembly logics within integral computational processes” [Menges 2009: np].

An excellent example is the ICD/ITKE ¹ Research Pavilion 2010. The project began by determining the characteristics of plywood including bending radii and associated stresses. According to the project information, “the computational design model is based on embedding the relevant material behavioral features in parametric principles. These parametric dependencies were defined through a large number of physical experiments focusing on the measurement of deflections of elastically bent thin plywood strips. Based on 6400 lines of code one integral computational process derives all relevant geometric information and directly outputs the data required for both the structural analysis model and the manufacturing with a 6-axis industrial robot” [ICD Website: np] ².

The basis of the structure is a pair of segmental arches. “These are connected in such a way that the tension and bending functions are divided into separate sections” [Kaltenbach 2010: np]. These pairs are arrayed to form a torus with an external diameter of approximately 12 metres. In this arrangement it was found that inherent stresses in the material increase the load-bearing capacity of the overall system. This made it possible to construct the entire pavilion from birch plywood strips only 6.5 millimetres thick [Kaltenbach 2010: np].

Structural analysis was carried out using FEM to understand how the material system would behave in relation to external forces such as wind and snow loads. The computational design model, FEM simulation and the built pavilion were then compared. It is concluded that the “integration of design computation and materialization is a feasible proposition” [ICD Website: np].

Director of the ICD, Achim Menges, has suggested that embedding material, structural and assembly logics into computational design tools promotes an understanding of “form, material and structure not as separate elements, but rather as complex interrelations in polymorphic systems resulting from the response to varied input and environmental influences and derived through the logics and constraints of advanced manufacturing processes” [Menges 2006: 78].

3.4 Summary

This chapter has sought to identify ways of better approaching the integration of design, analysis and construction using digital tools and technologies. I suggested that this endeavour may be better supported if material, structural and assembly logics are used to actively guide and inform early design exploration.

I noted that the quest for better informed computational design strategies is an active area of research, and identified performance based design as the contemporary paradigm associated with developing and deploying appropriate architectural design tools. I then elaborated on more relevant computational precedents focussed on material performance in architecture.
Each of the precedents I discuss serve to corroborate that materially informed computational design approaches may lead to better integration between design and production processes. Furthermore, they address what has thus far been perceived as a “tendency towards ... immateriality” (Picon 2005: 115) within computational design processes and outcomes by exploiting “new media that mitigate between the optimisation of structural designs and the enhancement of the architectural concepts” [Oxman and Oxman 2010:17] ².

In the next investigation, I test a specific structurally driven computational design approach, which relates mostly to eifForm and the Design | Analysis studies carried out by Nicholas. This engineering oriented procedure, known broadly as Topology Optimisation, seeks the most efficient distribution of material in response to applied forces by gradually removing under-utilised parts of a predetermined structure. Investigation B aims to test whether Topology Optimisation - a generative design approach informed by material and structural logics - can better support the quest to integrate design, analysis, manufacture, and assembly in architecture.

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3. Picon notes, “Cecil Balmond’s claims to cooperate fully in the design process, instead of being confined to mere structural calculations, is representative of the new perspectives that arise from a world blurring the distinction between mathematical abstraction and spatial concreteness” (Picon 2005: 120).
INVESTIGATION B
From Product to Process

B1 Introduction
B2 Topology Optimisation
B3 Study One: SpecifiCity
B4 Study Two: Strange Attractor
B5 Study Three: Calibrating Generative Results
B6 Findings
B7 Summary
B1 Introduction

In the previous chapter I suggested that computational approaches to architectural design could benefit if material, structural and assembly logics are implemented as design parameters within digital representations. I identified that the development of better informed digital design tools is an active area of research broadly associated with performance based design principles. I analysed a series of more specific precedents focussing on material performance and illustrated how this research serves to corroborate that materially informed computational design approaches may lead to better integration between design and production processes.

This section - Investigation B: From Product to Process - describes my engagement with an engineering-led design approach known as Topology Optimisation. The broad aim is to test whether materially and structurally informed design tools can better support the quest to integrate design, analysis, manufacture, and assembly in architecture.

An initial study looks at combining topology optimisation with additive fabrication in order to produce context specific architectural components with a high strength to weight ratio. A second investigation employs a more sophisticated version of the algorithm to inform a speculative design for a small pavilion. The third component demonstrates how truss-like physical models can be used to test and calibrate results from structural topology optimisation.
B2 Topology Optimisation

Topology optimisation is the generic term for a family of processes that make use of Finite Element Analysis (FEA) to determine materially efficient structural forms based on applied physical loads and constraints. Professors Mike Xie (RMIT University) and Grant Steven (University of Sydney) originally introduced the methodology in a paper titled Shape and layout optimization via an evolutionary procedure (Xie and Steven 1992). A more inclusive discussion of the ways in which topology optimisation could be applied to structural mechanics and engineering problems was subsequently described in their seminal book Evolutionary Structural Optimisation (1997).

Topology optimisation is a relatively simple algorithmic procedure that incrementally evolves a specified geometry toward optimal material distribution in response to applied forces. It involves the gradual removal of inefficient material based on initial conditions with regards to geometry, material properties, loading and constraints. In a reversal of the process, it can also be used to ‘grow’ structures within a predefined volume by adding material to regions of peak stress. Topology optimisation thus “seeks the most efficient use of material by altering the shape, topology and geometry of the structure and its various elements” (Felicetti 2009: 52). While the examples presented in this section focus on structural applications, topology optimisation can also be used to determine optimal structures in response to other forces such as heat, magnetism and vibrational frequency (Li et al 2001, Yoo & Kikuchi 2002, Olhoff & Du 2005, Akl et al 2009, Rubio et al 2011).

Topology optimisation is strongly related to principles of evolution and self-organization of living creatures, adapted from an engineering standpoint (Sasaki 2007, Ohmori 2008, Burry et al 2004). This understanding correlates with the findings of theoretical physicist and biomechanics engineer Professor Claus Mattheck who coined the Axiom of Uniform Stress (Mattheck and Breloer 1994: 13) to describe the way “trees adjust their growth ... [so] that the stresses on the surface are equally distributed” (Quint 2001: 1). As trees grow, regions enduring a disproportionate amount of stress are reinforced through the addition of material, while under-utilised areas naturally decay to avoid unnecessary ballast. This dynamic bidirectional redistribution of material approaches a state of uniform stress (ie. all parts of the material doing an equal amount of work as opposed to some doing more and some less). Mattheck’s research serves to corroborate D’Arcy Thompson’s seminal work On Growth and Form (1917) where he states “the form ... of any portion of matter, whether it be living or dead, and the changes in form which are apparent in its movements and in its growth, may in all cases alike be described as due to the action of force. In short, the form of an object is a "diagram of forces"” (Thompson 1917: 16).

For structural applications, topology optimisation requires a volumetric geometry with known material properties, design-specific points of loading and restraint, and the definition of fixed, ‘non design’ geometry (if required). FEA is used to identify material stresses and deformations, following which under-utilised parts of the structure are deleted. This process is repeated between 10 and 100 times or until a specified percentage of the structure remains. In theory, the result is an optimally directed ..., constraint compliant geometry with a high strength to weight ratio and a “direct and rational connection between form and material” (Felicetti 2009: 52).

1. In Approaches to Interdependency: early design exploration across architectural and engineering domains (2008), Dr. Paul Nicholas discusses how the concept of optimisation may be better understood in terms of an optimally directed or ‘aptimized’ (a term borrowed from Makoto Sei Watanabe) design process (Nicholas 2008: 109-110).
A number of topology optimisation tools have been developed around the world. Xie and Steven initially developed Evolutionary Structural Optimisation (ESO) and provided a 2D implementation to accompany their book named Evolve97. Japanese structural engineer Mutsuro Sasaki has developed his own implementation of the algorithm called Extended ESO (EESO), which he used to develop the structural scheme for Qatar’s national convention centre – currently under construction (Sasaki 2007). Another research group in Japan headed by Professor Hiroshi Omhori used similar methods to design the Akutagawa River Side building (Omhori 2008). Matthiexc has devised a list of relevant algorithms which he calls Soft-Kill Option (SKO) and Computer-Aided Optimisation (CAO) (Quint 2001). Phillipe Morel from EZCT Architecture and Design Research has developed an equivalent code for use with Mathematica (Morel 2004). Ole Sigmund et al. maintain a series of web-based structural optimisation applets named TopOpt 2, and Panagiotis Michalatos & Sawako Kajima (Sawapan) have developed Topostruct – a freely available program for Windows OS. Over and above this list of standalone software modules [which is by no means exhaustive], an increasing number of sophisticated engineering tools incorporate similar algorithms and procedures.

Since its introduction in the early 1990’s, topology optimisation has come to be widely used in the automotive, aeronautical and naval industries where there is a strong focus on performance criteria such as strength to weight ratio. In the context of architectural design, topology optimisation is still rare. Consequently, the implications of using topology optimisation as a design tool have yet to be fully described as very few designers or architects have had direct access to such algorithms. Although the coupling of additive fabrication with traditional metal casting is by no means exhaustive, an increasing number of sophisticated engineering tools incorporate similar algorithms and procedures.

TopOpt and Altair’s Hyperworks platforms, which is packaged together with SolidThinking and is available as an additional work bench for Catia.

In addition, Bidirectional Evolutionary Structural Optimisation (BESO) was developed by the Innovative Structures Group at RMIT University and released as a plug-in for Rhinoceros in October 2010.
Description

The context for this speculative study is a popular music venue located in the suburb of St Kilda, Melbourne. A large and obtrusive concrete column interferes significantly with views toward the performance stage. This location was chosen as it provided a simple and realistic design problem that might be solved using a combination of the tools and techniques identified above. Due to the structure of the building complex, complete removal of this column is prohibitively expensive. Instead it is reasoned that replacing the unappealing homogenous pylon with a structurally differentiated element would ease much of the visual interference and function as a striking design feature.

As a technical study SpecifiCity has two distinct agendas. Firstly it serves as a platform for developing a deeper understanding of topology optimisation in particular and materially informed computational design in general. Secondly it provides a framework to explore how additive fabrication might be used to produce geometrically complex structural components.

The outcomes from this study have been presented at the Association of Architecture Schools of Australasia (AASA) conference in September 2007, and at the Association for Computer Aided Design in Architecture (ACADIA) conference in October 2008. They have further been exhibited and published as part of Homo Faber, an Australian Research Council grant exploring the role of physical models in contemporary architectural design.

Design Logic

To initiate this study, I obtained a copy of Evolve97 from Professor Xie. Practical mastery of the software enabled me to develop a preliminary understanding of the way in which design intent might be abstracted as a set of initial structural conditions.

Throughout this explorative process it became apparent that orthogonal geometries are not the most materially efficient way of resisting structural forces. My initial experimentation with structurally driven topology optimisation revealed that material efficiency is perhaps better achieved using less obvious configurations and geometries resembling those found in nature.

6. Professor Mike Xie has been head of the School of Civil, Environmental and Chemical Engineering at RMIT University since 2005. He initiated the Innovative Structures Group (ISG) together with Peter Felicetti of Felicetti Pty Ltd Consulting Engineers. ISG is focussed on enhancing collaboration and innovation in architecture and engineering.

Figure B3a
Recurring characteristics of Evolutionary Structural Optimisation (ESO):

1. Periodic structures
Analogous structure in nature: Venus’ flower basket
During my initial explorations two recurring features were observed. Firstly, uniformly distributed loads tend to generate periodic structures (Figure B4-3a). Secondly, eccentric loading and support conditions tend to form branching structures (Figure B4-3b). Further experiments revealed a third distinctive tendency referred to in associated literature as checkerboard pattern (Figure B4-3b). Huang and Xie note in their latest book, “the presence of checkerboard pattern causes difficulty in interpreting and manufacturing the ‘optimal structure’” (Huang and Xie 2010: 19). Unaware of this inconsistency, I interpreted the checkerboard effect as a kind of ‘structural filigree’ – an ambiguity associated with the density of the finite element mesh rather than a problem with the algorithm. This misguided analysis prompted an idea to use topology optimisation at both macro and micro scale. As it turns out, this idea is consistent with the views of a number of other researchers in the field (Sigmund 1995, Torquato et al. 2002, Zhou and Li 2008). Huang and Xie observe, “not only can the topology optimisation techniques be applied to large-scale structures such as bridges and buildings, they may also be used for designing materials at micro- and nano-levels” (Ibid: 2).
The aim of exploring Evolve97 was to become familiar with how topology optimisation might be used as a generative tool for design. The original intention for this study was to utilise a three-dimensional version of the algorithm to inform the design process. At the time however (2007), working in 3D was a far more complicated matter than in 2D as it required intimate knowledge of FEA software (Figure B3-4c). Since one of aspirations of this study was to explore how additive fabrication might be used to produce geometrically complex structural components, I chose to alter my design approach to move the investigation forward in a timely manner.

My experimentation with Evolve97 helped to reveal the form generating tendencies of topology optimisation procedures. I appropriated the recurring characteristics noted earlier to inform a 3D model created using Rhinoceros and Surface Evolver. In addition, based on the observations made during initial experimentation, a sub-optimisation schema was developed. This strategy achieves a further level of material optimisation at the level of surface.

For the purpose of this study, the sub-optimisation logic has been derived from the deep-sea sponge Euplectella Aspergillum (Venus’ flower basket). This sponge is made of very fine silica yet has a particularly robust structure due to the three-dimensionally interwoven bracing that forms its skeleton (Figure B4-3a). This particular structural configuration was specified as it reflects the tendency of topology optimisation to produce periodic structures under uniformly distributed stress and provides an appropriate level of geometric complexity and intricacy to justify an exploration into new modes of fabrication.

Whilst I originally sought to use topology optimisation to directly inform the new column design, the 2D nature of Evolve 97 and the complexities involved in deploying a 3D variant of topology optimisation restricted the extent to which I was able to fulfil my initial goals and expectations. Despite this, I believe that the proposition I developed via alternate modelling methods does give some idea of what might be achieved if material, structural and assembly logics are treated as parameters with which to inform early design exploration.

Figure B3d Speculative column proposal: form generation and initial sub-optimisation schema based on Venus’ flower basket structure
Figure B3e Specific digital models illustrating extreme scales of structural optimisation

Figure B3f Specific physical models illustrating extreme scales of structural optimisation
Fabrication Logic

One of the initial limitations that must be considered when using topology optimisation as a generative design tool is that the results often challenge traditional methods of fabrication due to their geometric complexity. In addition, while sub-optimisation strategies might achieve additional reduction of material and weight, the intricacy of the resulting geometries further challenge conventional manufacturing processes.

The most appropriate way of directly fabricating the structural forms that emerge through the use of topology optimisation is additive Rapid Manufacturing (RM). Additive RM utilises CNC technologies to directly produce functional components in a variety of materials (metals, plastics, ceramic composites). However, at the scale required for architectural construction additive RM is not yet commercialised. To overcome this limitation, Specifit explores a means to indirectly manufacture architectural components using a combination of additive fabrication and traditional metal casting.

- **Cast Metal in Architecture**

Prior to the development of reinforced concrete and industrially manufactured rolled and extruded steel during the late 19th century, cast iron proved to be useful as a way of producing strong and lightweight structural elements that freed architects from heavyset masonry construction. A noteworthy example of cast iron construction is the **Crystal Palace** designed by Joseph Paxton for the London World’s Fair in 1851. In America, the mechanic/inventor James Bogardus was pivotal to the widespread introduction of cast iron architecture and construction during the same period (Gayle 1998). **Hôtel Tassel** (1892) by Victor Horta and the **Paris Metro** entrances by Hector Guimard are two particularly striking further examples that exhibit a playful use of cast iron structural systems.

The Neo Gothic Revival of the nineteenth century eventually prompted a more prosaic use of elaborate and complex geometries cast in metal. The flexibility and strength of cast iron freed designers to create new structural forms impossible in stone. An elegant example is Calvert Vaux’s cast-iron bridge (1860) in Central Park, New York, which is supported by forms derived from Gothic blind arcading and window tracery.

Although twentieth century industries have developed better casting materials and more efficient processes, the difficulty and primary expense involved in casting has always been the production of tools, patterns and molds (Stacy 2001). The tradition of metal casting has therefore developed into a specialized craft primarily used for bespoke production or to achieve economies of scale.

While cast metal objects are common within architectural detailing, hardware and decorative elements, it is rare to see cast metal used for structural purposes in contemporary architecture. Notable exceptions are the cast steel **gerberettes** of the **Centre Georges Pompidou**, Paris (1971–1977). These considerably sized elements demonstrate it is feasible to produce large-scale cast metal components and deploy them within architectural structures.

- **Digitally Fabricated Casting Tools and Patterns**

CNC technologies alleviate some of the difficulties in manufacturing casting tools for complex geometries. The automotive, aeronautical and jewellery industries have utilized these technologies for some time. Intricate machine made patterns and molds are increasingly commonplace in the foundries and workshops that service these industries (Schodek et al 2005).
Although CNC manufacturing platforms are currently limited in size, large and complex components can be subdivided and assembled in sections. For example, a number of CNC milled foam pieces can be assembled to form large investments for a process known as Lost Foam Casting (LFC). In the automotive industry, this methodology is used to create cast aluminium engine blocks. Architect Kevin Rotheroe has demonstrated the feasibility of applying similar techniques to produce a series of structural steel frame components (Rotheroe 2000).

• A Strategy for Manufacturing SpecifCity

To determine a feasible strategy for manufacturing the proposed column design, it was necessary to investigate a variety of different tool making and casting methods. One of the challenges was that the fabrication strategy had to support a high degree of detail, extreme geometric complexity and large-scale production.

The lost-wax casting method used in Investigation A has all the qualities required except that in today’s industries, the resulting objects are typically limited to around one cubic metre and/or between 200-250kg. A process called sand casting on the other hand supports parts weighing up to five tonnes but is exceptionally limited in terms of geometric complexity due to the fact that reusable patterns must be removed from the sand prior to casting. LFC is a relatively recent evaporative casting technique that combines the geometric flexibility and accuracy of lost wax casting with the scale of sand casting. In this process, an expendable polystyrene pattern is embedded in sand. Molten metal is poured into the assembly vaporising the foam and taking on its form.

At present there are geometric limitations with regards to making the expendable foam investments that are necessary. Usually they are made via subtractive processes like hand sculpting, CNC milling and hot wire cutting, or by a process similar to injection molding.

The problem with these methods is that none of them support the level of detail or geometric complexity required by the column design and/or they produce a large amount of waste.

To address a similar set of issues, an American company named Extrude Hone formed a joint venture with General Motors and MIT in 1997 to develop a 3D printing process to improve LFC in the automotive industry. The consortium aimed to develop additive fabrication systems to manufacture polystyrene patterns of engine components, thereby reducing production time and alleviating the difficulty of producing complex casting patterns (Status Report 2006: np). They managed to produce a number of prototype machines and successful examples, but eventually turned their attention to direct metal printing and the production of ‘patternless’ sand molds for direct casting. As a study into streamlining and enhancing automotive component manufacturing, we can gather that at some point it became apparent to those undertaking the research that additive fabrication could make a series of other time-consuming and frustrating tasks in the foundry obsolete by overcoming the need for patterns altogether.

In 2005 the research arm of Extrude Hone was formed into a company called ExOne. ExOne are the vendor for two related products; ProMetal and ProMetal RCT. The ProMetal system supports direct metal printing. It produces ‘green’ metal objects that require firing and alloy infiltration to become functional prototypes. Alternatively, ProMetal RCT (Rapid Casting Technology) binds layers of sand to create molds with integrated cores suitable for directly casting light metals, non-ferrous metals, iron and steel. The largest of their machines (S-Max) has a maximum build volume of 1800 x 1000 x 700mm and produces high-resolution parts with a layer thickness of 0.28 – 0.5mm.
This approach to manufacturing casting tools has since been appropriated by other companies wishing to enter the rapid casting market. For example, 3Corp 3D printers support a proprietary printing material (ZCast 501) that acts like casting sand and can be used to produce patternless molds for direct casting of nonferrous metals. This methodology and others like it have come to be known generally as \textit{patternless casting}\textsuperscript{8}. A video of the ProMetal RCT process can be viewed online\textsuperscript{9}. It demonstrates the typical mold fabrication, assembly, casting and analysis procedures required to manufacture cast engine blocks using patternless casting.

\textbf{Casting Bespoke Architectural Components} 

Investigation A demonstrated that additive fabrication combined with conventional investment casting processes is a practical methodology for indirectly manufacturing intricately detailed industrial scale objects. Deploying an analogous fabrication logic at the scale of architecture is more of a challenge but appears feasible due to the increasing size of additive manufacturing platforms.

As noted earlier, the potential of lost wax casting is restricted to a relatively small scale. It is most suitable for fabricating intricate components under one cubic metre and no heavier that 250kg. I believe that presently the most fitting technique for casting large-scale, complex and intricately detailed architectural components is Lost Foam Casting (LFC). To explore ways of streamlining and simplifying LFC pattern production, research into additive polystyrene printing was initiated by the United States automotive industry in conjunction with MIT. This research rapidly evolved into what has become known as patternless casting or rapid casting technology.

With patternless casting, instead of producing a foam pattern that must subsequently be embedded into sand, sand-based casting media is used to form a patternless mold into which molten metal can be poured directly.

While this approach has revolutionised the automotive industry by accelerating turn around times during research and development, patternless casting is currently feasible only for architectural projects with a more or less unrestricted budget since the same economies of scale do not apply in building construction.

To conclude, combining additive fabrication and metal casting could enable the production of intricately detailed customised building components. This approach may be helpful for architects, engineers and builders grappling with or interested in manufacturing bespoke architectural components that might be assembled to form more materially efficient architectural structures. Unfortunately, creating a series of unique components in this manner is presently beyond the budget of typical architectural projects. A more pragmatic approach might be to use additive fabrication to manufacture a master pattern that can be easily reproduced using less expensive techniques. Investigation A explored this idea at the scale of jewellery. The cast steel elements of the Pompidou Centre\textsuperscript{10} served as an example of how such an approach might be scaled at the architecture.

\textbf{Synopsis} 

At this point, it was suggested by a review panel\textsuperscript{11} that the Specif[city] project be discontinued as it had fulfilled my stated goals, which were to test the generative potential of topology optimisation and investigate an approach to manufacturing the resulting components. Rather than continue towards the production of a full-scale prototype, which was my intention, the panel felt that I should explore the deeper implications of generative design strategies. In particular, they drew attention to my insights around the recurring structural characteristics observed under various loading conditions, prompting the question: could generative tools help architects gain a deeper understanding of material performance and thereby facilitate a more coherent design to production workflow?

10. It is relevant to note that Renzo Piano - one of the architects involved in conceiving the Centre Georges Pompidou - has written in his log book: “Knowing how to do things not just with the head, but with the hands as well: this might seem a rather pragmatic and ideological goal. It is not. It is a way of safeguarding creative freedom. If you intend to use a material, a construction technique, or an architectural element in an unusual way, there is always a time when you hear you have you hear there is always a time when element in an unusual way, technique, or an architectural a material, a construction freedom. If you intend to use of safeguarding creative goal. It is not. It is a way programmatic and ideological with the hands as well: not just with the head, but “Knowing how to do things in conceiving the Centre 10. it is relevant to note Casting: A New Design Paradigm, World Market Series Business Briefing www.soligen.com/variable/patternless/patternless.shtml 9. ProMetal RCT Rapid Prototyping and Digital Sand Casting Services www.youtube.com/ watch?v=ZBVMaN9HGU 8. A video of the ProMetal RCT process can be viewed online. It demonstrates the typical mold fabrication, assembly, casting and analysis procedures required to manufacture cast engine blocks using patternless casting. 7. Casting Bespoke Architectural Components Investigation A demonstrated that additive fabrication combined with conventional investment casting processes is a practical methodology for indirectly manufacturing intricately detailed industrial scale objects. Deploying an analogous fabrication logic at the scale of architecture is more of a challenge but appears feasible due to the increasing size of additive manufacturing platforms.

As noted earlier, the potential of lost wax casting is restricted to a relatively small scale. It is most suitable for fabricating intricate components under one cubic metre and no heavier that 250kg. I believe that presently the most fitting technique for casting large-scale, complex and intricately detailed architectural components is Lost Foam Casting (LFC). To explore ways of streamlining and simplifying LFC pattern production, research into additive polystyrene printing was initiated by the United States automotive industry in conjunction with MIT. This research rapidly evolved into what has become known as patternless casting or rapid casting technology.

With patternless casting, instead of producing a foam pattern that must subsequently be embedded into sand, sand-based casting media is used to form a patternless mold into which molten metal can be poured directly.

12. Continued
Figure B3j
SpecifiCity sub-optimisation schema; physical model detail
B4 Study Two: Strange Attractor

Aim
Strange Attractor is a design proposition for a small restaurant and bar. The study was devised as a way of addressing the questions raised during my review. As such, it explores the extent to which topology optimisation might help architects cultivate a better awareness of structural behaviour and material possibilities. It is reasoned that the iterative nature of the generative process could allow an intuitive understanding of structurally optimised forms to develop. In turn, this sensibility could better inform architectural design conception and facilitate a more coherent design to production workflow.

Rationale
My applied research has thus far focussed on engaging with computational design tools and advanced CNC manufacturing processes to determine if they can facilitate more design control through better integrating design and production. I have found that pivotal to this quest is a deeper and more engaged understanding of materials, structures and processes of materialisation, as well as the consideration of these factors at the earliest possible stage.

SpecifiCity initiated my engagement with materially informed computational design. I described how understanding the potentials and tendencies of topology optimisation during the conceptual phase was critical to the final design outcome and the unfolding of fabrication logic. I found that beyond enabling the development of innovative and contextually specific architectural componentry, design strategies such as topology optimisation might actually allow architects to gain deeper insight into the behaviour and capacities of material constructs, which could in turn further inform design exploration and decision making.

Strange Attractor is devised as a way of further exploring this idea.

Description
Strange Attractor is a speculative design for a small pavilion located at a vineyard in South Eastern Victoria. The pavilion functions as a bar, restaurant and ‘cellar door’. Bi-directional Evolutionary Structural Optimisation (BESO) - a specific topology optimisation algorithm - is utilised to develop the structural ‘spine’ of the pavilion. This study carried out as an ‘in-house’ research project within Mese design studio, of which I am a practice partner.

The departure point in terms of design intent is the Lorenz Attractor – a mathematical mapping introduced by Edward Lorenz to describe and represent the behaviour of non-linear dynamical systems which evolve over time in a complex, non-repeating pattern. In this study, the Lorenz Attractor is used as a conceptual framework with which to organise the spatial, circulatory and functional logic of the pavilion around the two primary functions (attractors) of bar and restaurant. It is important to note that this diagram is used only as an organisational device and not as a source of formal inspiration.

This project has been exhibited in both national and international architecture exhibitions including; Homo Faber Exhibition 2008, 3rd Beijing Architecture Biennale 2008, Venice Architecture Biennale 2008 and The Nascent Present 2009. The work has also been published in Abundant (2008), Contemporary Digital Architecture: Design and Techniques (2010), and conference papers for AASA (2007) and ACADIA (2008).
Design Development

Re-purposing optimisation and analytic tools for architectural form finding requires abstraction of design intent into a set of geometric and force-based parameters and constraints. The challenge is to develop explicit formulations of geometry, loading conditions and supports that reflect the qualitative goals of architecture while respecting pragmatic constraints of engineering and fabrication. Initial experimentation with BESO revealed that minor changes to these initial conditions can have significant geometric consequences (Figure B4b) suggesting that the use of such tools for architectural design requires deliberate experimentation to proceed meaningfully. The preliminary design phase for Strange Attractor thus entailed numerous iterations in order to identify a strategy that (at least partly) satisfied both design and engineering objectives. Following are descriptions of three approaches explored, including the final design strategy:

- **Strategy One - Initial Experimentation**
  
  To initiate this study it was necessary to define a ‘design domain’ in the form of a primitive geometry that could house both the structure and functions of the pavilion as well as reflect the design intent. At this point I was still familiarising myself with BESO and thus my focus was more on exploring the algorithm than staying true to the design and site constraints. I began with a series of simple studies aimed at developing a general sense of design potential and an understanding of how to guide the BESO process from a design perspective.

  Abaqus CAE was used to define the initial geometry, loading and support conditions. The FEA/BESO models were set up to evolve a structural form primarily in response to uniformly distributed wind loads.
Numerous options were explored by varying the support conditions, and geometric outcomes were ‘guided’ by adding point loads in specific areas. Whilst this was a worthwhile exercise in terms of familiarisation and software fluency, results from this series of explorations failed in one way or another to accommodate the functional and spatial goals and requirements of the pavilion.

• **Strategy Two - Introducing the Parti**
  At this point the Lorenz attractor was introduced as a basis for deriving the circulatory and spatial logic of the pavilion. The reason behind this choice of diagram was that it acknowledges the pavilion as a backdrop to a dynamic experience in which visitors oscillate around the primary attractors of bar and restaurant in a complex, non-repeating pattern.

  To embed this intent within the FEA/BESO model required reconsideration of the initial geometric primitive. A simple rectangular prism was chosen as an new starting point to reflect the desired programmatic and circulatory layout as well as to emphasise privileged views towards the vineyards. Two voids were introduced in the volume to reflect the organisational logic of the pavilion and locate the attractors. Wind was initially considered to be the primary generative force. Altering the configuration of supports produced differing results (Figure B4d).

  It became clear that the minimally constrained nature of the site for this study presents somewhat of a challenge in terms of deploying topology optimisation. My experimentation revealed that the stresses induced by wind and self-weight alone are not sufficient to generate a structure that can accommodate the spatial, circulatory and functional logic of the pavilion. I found that this was mainly due to the fact that the positioning of internal structural elements often conflicted with my spatial desires and functional goals.

• **Strategy Three - Phantom Loads**
  From my experimentation I was aware that results from topology optimisation can be geometrically manipulated by adding additional loads to specific areas, introducing ‘non-design’ geometry or voids and altering the configuration of supports. To overcome the issue of working in an unconstrained context, I introduced a series of what I call *phantom* loads to guide the design outcome towards architectural goals (Figure B4e). The final design strategy for the pavilion included a combination of uniformly distributed wind loading and numerous phantom point loads located on the edges and corners of the structure (Figure B4f).

  The introduction of loads that do not correspond faithfully to practical loading conditions became a way of manipulating geometry towards architectural goals, but obviously detracted from the efficiency of the structural solution. In other words, the final design is *sub-optimal* since achieving functional and spatial goals was possible only by compromising engineering goals to some extent. My findings are in line with the observations of Paul Nicholas who describes this design vs engineering trade-off as resulting in ‘optimally directed’ or ‘optimised’ design processes (Nicholas 2008: 109).

• **Final Proposition**
  The pavilion takes form via the incremental refinement or ‘tuning’ of exogenous forces and endogenous constraints relating to material properties and points of restraint. A consistent connection is thus maintained between the artefact and the processes that bring it into being. Strategy three produced a sinuous structural spine that divided the initial geometry into two distinct spaces and supported the desired circulation logic. The attractors, which were originally encoded as void spaces, became integrated with the structural spine as skylights that enlarge to form curvaceous cavern-like spaces on the interior.
The solid geometry that emerged from the BESO process required a significant amount of interpretation and translation to become a realistic design proposition. Firstly, it was analysed to determine feasible sub-optimisation and fabrication strategies. The use of additive fabrication was ruled out due to its inaccessibility and excessive cost at the scale of architecture. Instead, a laser cut timber and steel framing solution was developed to minimize material usage and increase the strength to weight ratio of the final structure. To address fabrication considerations such as method and complexity of assembly, the resolution of the digital model was significantly decreased to ensure components were of a size suitable for manufacturing and installation. This strategy enabled a coherent link between the geometrically complex structural spine and its (more or less) rectilinear boundary.

The resulting proposal consists of a glazed envelope supported by triangulated mullions that enable a seamless transition between skin and primary structure. In contrast to the angular exterior tectonic, internal spaces smoothly transition between floor, bar, wall, ceiling and structure. The expressive structure maximises the open plan nature of the pavilion and enhances the spatial experience. Over time it is envisaged that creeper vines will climb the structure until the pavilion merges seamlessly with the visual tapestry of the vineyard.
Synopsis

Whilst the outcome from this investigation has been well received by colleagues and design critics, the study itself fails to shed much light on how topology optimisation might enable architects to cultivate a better awareness of structural behaviour and material possibilities.

There are four main reasons why. Firstly, as this was an architectural investigation carried out within a practice context, there was a limited amount of time that could be devoted to generative design. Secondly, since BESO and the corresponding FEA program were both new to me, mastering the software occurred alongside the conceptual design phase. This limited the extent to which I was able to carry out useful experiments as much time was spent becoming familiar with the interfaces and getting the software to work properly. Thirdly, as I found early on in my experimentation and illustrated in Figure B4b, a minor local change can significantly alter global results. This makes it very difficult to identify and trace connections between specific causes and effects. Lastly and perhaps most importantly, I had no way to test or calibrate the optimisation results to verify they would behave as they should.

Despite failing to contribute significantly to my re-oriented trajectory, the Strange Attractor study points to the capacity for generative techniques to assist in developing unexpected and potentially beneficial design solutions. Generative methodologies such as topology optimisation thus engage the computer as a design partner rather than simply as a sophisticated drafting aid. At the same time however, this project reveals how such tools can be easily misappropriated during the early design phase to produce complex architectural geometries that do not necessarily fulfil specified performative criteria.
B5 Study Three: Calibrating Generative Results

Aim
To address the shortcomings and limitations encountered during the previous study, this research component explores how the results of topology optimisation might be rapidly tested and calibrated using basic physical models. The objective is to probe deeper into the notion that topology optimisation might help to develop a better understanding of structurally optimised forms and material potentials.

Rationale
Investigation A demonstrated that the ability to cycle rapidly between digital and physical media in meaningful ways is central to gaining a better understanding of the critical factors involved in design and production processes. While the SpecificCity and Strange Attractor studies were carried out in an iterative manner, their design processes relied solely on feedback from computational simulation, analysis and visualisation. The physical models that were produced via additive fabrication were for representational purposes and thus operated as 3D physical facsimiles that contributed little to enhancing my understanding of their structural behaviour.

To develop a better understanding of structural and material potentials, it may be beneficial if the results from generative processes are tested and calibrated against physical prototypes that behave in a similar manner. In this way the findings from physical modelling could be fed back into the following computational iteration so that as the design process progresses, a partly technical and partly intuitive alignment between design, optimisation and fabrication processes might emerge.

While a rapid feedback loop between digital and physical media is an ideal scenario, one of the particular limitations I found when using BESO during the early design phase was that input data must be defined using complex engineering analysis software. This cumbersome way of defining initial conditions and the time required to obtain results from the analysis process makes this particular implementation of topology optimisation frustrating from a design perspective and limits the extent to which it can be meaningfully engaged during early design exploration.

To overcome these limitations, this study utilises Topostruct - a standalone topology optimisation program which is less accurate than BESO but provides much faster feedback (seconds for low resolution and minutes instead of hours for high resolution models). This characteristic makes Topostruct more suited to conceptual stages of design when “the designer’s imagination is at work to capture different design possibilities” [Attar et al 2009: 234]. While accuracy is important when implementing generative simulation and analysis tools in design, it is reasoned that physical calibration of the results from Topostruct will help to address any analytic errors.

Description
This research has been undertaken primarily within a university design studio setting where I introduced the concept of calibrating topology optimisation results to a class of approximately 15 undergraduate students. The outcomes from these explorations are a series of digital models and corresponding physical structures.
This study stems from my observation that topology optimisation effectively produces truss-like structures that can be interpreted and materialised using simple materials. These quick physical prototypes could enable rapid evaluation and verification of structural behaviour.

Topology optimisation was introduced to participants through a series of physical and digital modelling exercises. These exercises familiarised students with the Topostruct interface and helped them establish a way of distilling the results into useful physical models.

The procedure can be described as follows:

1. Define an initial geometry and boundary condition (points of loading and restraint) in Topostruct
2. Generate optimised solution
3. Translate solution into 3D truss structure using simple materials such as bamboo skewers, masking tape and foamcore
4. Verify result using analogous boundary condition and forces
5. Identify points of weakness and unexpected opportunities by testing alternate forces
6. Use this feedback to drive further design iterations

An initial investigation required students to produce a series of more or less random structures using Topostruct. They were then required to analyse the results and construct corresponding physical prototypes. The resulting models were tested for strength and stability. These structures proved robust when loaded and restrained in a manner analogous to their digital counterparts. Although Topostruct is less precise than BESO, this process verified that the results are sufficiently accurate to meaningfully inform early design exploration and further iterations.

Following this initial exercise, students were given two weeks to design a pedestrian footbridge between two buildings in the Melbourne CBD using a combination of topology optimisation, digital and physical modelling (Figure B5b). This task required them to implement the earlier experimentation within a more directed architectural investigation. The particularly challenging aspect was determining a suitable initial set of geometric and force-based conditions capable of embodying design intent. Students iterated through a series of digital and physical models until a suitable negotiation of structure, form and function was found.

In most cases, the outcomes were exceptional given the short time frame allotted and the relative inexperience of the students in both generative processes and design in general. The design outcomes demonstrate a good understanding of how topology optimisation might be used to generate interesting and unexpected structural forms suited to architecture.
Synopsis

The rapid feedback provided by Topostruct and the simple approach to verifying results produced an accelerated analysis – synthesis loop among students. By rapidly oscillating between digital and physical models they became familiar with the potentials, limitations and tendencies of topology optimisation over the course of a week. Through this digital-material feedback loop, students were observed to develop a good understanding of how to produce and test new structural forms suited to architecture. Alongside developing a deeper understanding of structural and material tendencies, this methodology revealed to the students how computation could be used innovatively and as a design collaborator rather than simply as a tool with which to execute a predetermined design vision.

Using physical models to verify generative results allowed students to deploy topology optimisation meaningfully to inform and expand their early design exploration and design refinement processes. This simple method illustrates how computational design tools with embedded material intelligence can be critically engaged and to meaningfully inform early design exploration in architecture. The design outcomes from the pedestrian footbridge exercise reveal that calibrating topology optimisation results with simple models is a useful generative technique which cultivates a good understanding of structural and material potentials, and can be utilised to actively inform architectural design towards rational, innovative, expressive and potentially more materially efficient structural configurations.

Figure B5c
Two propositions for a pedestrian footbridge developed using topology optimisation and simple skewer models.
Students:
Top - Nathan Crowe
Bottom - Errol Xiberras
B6 Findings

Digital-Material Calibration

The interest in using structurally driven topology optimisation in architectural design lies in the fact that it allows a ‘direct and rational connection between form and material’. In my first and second studies however, coupling this technique with additive fabrication allowed the translation between digital and physical media to be “almost too seamless, there is no hands-on intervention, so that no accuracy is lost, but equally no understanding is gained” (Hyde 2008: 147). This fluid and direct link from design to production was found to undermine the use of topology optimisation as a generative design tool since there was no way of verifying or calibrating the results from an engineering standpoint. As this investigation progressed, I found that making simple structural prototype models was a useful way of overcoming this issue. These quick to produce models were an invaluable way of testing and calibrating the various formal configurations suggested by the computer without relying on consultants, further software or advanced manufacturing. The tactile nature of building a structural prototype provides immediate feedback with regards to strength, stability and potential assembly methods, as well as whether or not all necessary structural conditions were accounted for in the generative digital model it is derived from.

This hands-on approach enables feedback from one medium to inform a following iteration in the other by revealing areas of potential weakness and acting as a way of identifying if and how a structure might be improved. Results from this process can be used in two ways. Firstly, to inform a further round of design exploration by suggesting a new and better starting condition. Secondly, for design refinement by revealing where and how further structural and material efficiency can be achieved. Examples of this are when the physical testing process illustrates that certain compression elements could be substituted for tensile cables, or that particular areas could benefit from extra reinforcement.

I observed that among the students to whom this materially informed approach had been introduced, the feedback loop between digital and physical media, and the structural clarification that emerged from this process appeared to cultivate a genuine understanding of how material, structure and form are interrelated and might be better integrated within their architectural designs. This suggests that linking digital and material prototypes may offer an avenue to better informed design exploration and a more coherent design to production workflow.

Rapid Results

The calibration component of this investigation revealed that obtaining rapid results is perhaps the key to integrating generative tools into the design process. It suggested that the faster the feedback from analysis, the more useful generative tools are for early design exploration. The three studies carried out during this investigation employed three different versions of topology optimisation that facilitate three very different modes of interaction. The first study - Specifi(City) - used a 2D implementation named Evolve97. The second study - Strange Attractor - utilised a 3D implementation named BESO. The final study introduced a less accurate version of the technique named Topostruct.

Evolve97 was useful in revealing structural tendencies and provided rapid feedback, however its simplicity restricted how I was able to use it to inform my design. BESO proved useful but exceptionally frustrating. Each experiment required approximately 10-15 minutes setup time and between 20-60 minutes to produce a result. This exceptionally slow process inhibited my investigations significantly. To overcome this limitation, towards the latter stages experiments were carried out using very low resolution meshes.
Study three showed that the accelerated feedback loop made possible by combining a lower accuracy optimisation tool with simple analogue modelling is a practical way of conceptualising innovative and robust architectural structures. Coupling rapid feedback from generative tools with rapid physical modelling enables results to be quickly evaluated and this new information to be fed back into the next design iteration. Utilising topology optimisation in this manner appears to facilitate a deeper understanding of structural and material tendencies, which in turn enables the calibration and refinement of forms towards design, engineering and construction goals.

Computer as Design Collaborator

Generative design techniques such as topology optimisation open architecture to new and exciting possibilities as computers can enter the design process as instrumental collaborators rather than simply as glorified drafting aids with which to implement preconceived designs.

Utilising topology optimisation requires design intent to be distilled into a set of initial conditions that negotiate design and engineering criteria. These include; preliminary geometry, load cases and support conditions, as well as specific design elements such as materials, voids and fixed regions. This way of expressing design intent differs considerably to the traditional ‘Design Parti’ in which intent is expressed as a static pictorial representation. Rather than thinking in terms of form, topology optimisation instead requires the definition of starting conditions that describe a flow of energy through a material system and thus requires architects to think in terms of force. My research demonstrates that this way of approaching architectural design leads to unexpected configurations and compositions that may in turn lead to increased building performance and better design outcomes.

B7 Summary

Investigation B - From Product to Process - has described my engagement with an engineering-led computational design approach known as Topology Optimisation. The aim has been to test whether this materially and structurally informed generative design approach can better support the quest to integrate design, analysis, manufacture, and assembly in architecture.

Study one demonstrated how topology optimization could inform the design of context specific and materially efficient architectural components and outlined how such components could be feasibly manufactured using a combination of additive fabrication and traditional manufacturing processes. The basic 2D implementation of topology optimisation I utilised revealed that informed design tools could help to develop a more pronounced understanding of structural and material tendencies that can in turn guide conceptual thinking and design refinement.

In study two, I attempted to use a 3D implementation to further explore whether materially informed computational design tools might cultivate a more acute awareness of structurally optimised forms and material potentials, and thereby facilitate a more coherent design to production workflow. Despite the interesting architectural outcome from this study, there were a number of limitations that prevented satisfactory investigation of the territory in question. In particular, I had no way of verifying or calibrating optimisation results in a rapid manner.

The third study aimed to rectify this issue by introducing a methodology to quickly and effectively test and calibrate the results from topology optimisation processes.

14. A more extensive discussion on this topic can be found in a paper that I presented at the ACADIA Conference in 2008 titled, An Energy Centric Approach to Architecture – Abstracting the Material to Co-rationalize Design and Performance (Frumar 2008).

Full paper can be found in the Appendix.
I found that setting up a tightly linked feedback loop between digital and physical media appears to cultivate a rapid and genuine understanding of structural and material behaviour. This finding suggests that a critical use of computational design tools with embedded material intelligence can help to broaden material and structural awareness during early design exploration, and is thus promising in terms of better integrating design, engineering and fabrication in architecture.

Reflecting on my journey through this investigation, I became aware that my initial intention to construct full scale prototypes - and thus explore first-hand if and how digital technologies might enable better integration between design processes and manufacturing strategies - had fallen by the wayside in order to gain deeper insight into the implications of materially informed generative processes. Furthermore, the particular branch of topology optimisation I was working with seemed limited in what it might offer architects in this regard due to the fact that assembly and construction parameters are not accounted for within the form generation process.

Investigation C, which I describe in the next section, evolved from a desire to address my original intentions and overcome the limitations of the tools I had been working with. Through an extensive process of physical and digital prototyping, I explore the potential for an integral computational design and manufacturing strategy in which material, structural and fabrication logics are implemented as design parameters within digital tools and serve to constrain early design exploration within a spectrum of rational and buildable structures and forms. In doing so, I aim to further test the hypothesis that a critical engagement of materially informed computational design tools might expand the material sensibilities of designers, and thereby contribute to more streamlined design to production processes in architecture.
INVESTIGATION C
From Process to System

C1 Introduction
C2 Tensegrity Structures
C3 3D Compressed Components
C4 Tensegrity Tools
C5 Interim Summary
C6 Design Studies
C7 Design Studies - Synopsis
C8 Summary
Investigation B suggested that critical engagement of materially informed computational design tools might help to expand material sensibilities among architects and potentially facilitate new and better design and production processes. To test this idea further and simultaneously explore a feasible approach to fabricating full scale architectural structures, Investigation C - From Process to System - embarks on an extensive process of physical and digital prototyping as a way of developing and implementing an integral computational design and manufacturing strategy.

The final study of Investigation B specifically demonstrated how topology optimisation results can be materialised as simple truss structures. This process was shown to help verify generative results and facilitate informed design refinement. Further to this, it also revealed that additional material optimisation is possible by manually analysing structures and identifying areas where compression struts may be substituted with tensile cables. This idea is of interest as a way of further reducing material consumption, increasing strength to weight ratio and better calibrating structural behaviour.

My desire to work in a more materially engaged manner and with spatial systems that incorporate tensile elements led me to a particularly fascinating family of lightweight prestressed self-stable networks known as Tensegrity structures. Although these structures exhibit a number of intriguing characteristics, they are perhaps most obviously unusual because they are freestanding yet compression elements are discontinuous and appear to ‘float’ in a sea of tensile elements. In other words, they appear to counterintuitively defy gravity.
Within investigation C. I interrogate tensegrity structures for their potential to support the integrated design and construction of complex, lightweight and self stable architectural forms. This Investigation is presented in two sections.

The first provides an overview of tensegrity structures and describes my initial engagement and physical experimentation. It goes on to describe a new class of tensegrity developed in collaboration with structural engineers from the Innovative Structures Group (ISG) at RMIT. I then identify a complimentary computational methodology capable of simulating their behaviour and thus establish a basis for a generative and integral design to production workflow. The second component implements the aforementioned research within a series of speculative and practice based architectural studies.

The outcomes from this investigation have been published in the Journal of the International Association for Shell and Spatial Structures (Frumar et al. 2009), and presented at the ACADIA (Frumar & Zhou 2009a) and ECAADE (Frumar & Zhou 2009b) conferences in 2009. They were also included in Make it work: Engineering possibilities - an exhibition at the Center For Architecture in New York in January 2009. Finally, one of the design studies presented later – (near) Instant Highrise – received an honourable mention in the annual international Evolo Architecture Magazine competition in 2009.

C2 Tensegrity Structures

An Overview

The word ‘Tensegrity’ “is a portmanteau of ‘tensional integrity’. It refers to the integrity of structures as being based in a synergy between balanced tension and compression components” [Wikipedia Contributors 2010: np]. Tensegrity structures comprise of a series of discontinuous compressed elements contained within a ‘sea’ of continuous tension. These freestanding pin-jointed truss-like systems typically consist of elements that are either in pure compression or pure tension. It is commonly thought that “since the compression members do not have to transmit loads over long distances, they are not subject to the great buckling loads they would be otherwise, and thus they can be made more slender without sacrificing structural integrity” [Burkhardt 2008: 29]. In tensegrity structures, slender compression elements and prestressed tensile cables operate in unison to create lightweight yet robust self stable configurations.

Tensegrity structures exhibit a number of characteristics that correspond to behaviours observed in nature across a number of scales. Tensegrity logic – discontinuous compression within continuous tension – has been used to describe the configuration of the universe [Fuller 1975], the physiology of the human body [Levin 1982] and the structural behaviour exhibited by carbon atoms, water molecules, proteins, viruses and other biological cells [Ingber 1997]. Richard Buckminster Fuller viewed tensegrity as nature’s grand structural strategy [Sadao 1996].
Architectural Interest and Potential

Tensegrity structures are of considerable interest as a way of constructing lightweight, rapidly deployable and geometrically complex structures in a modular manner. Following are selected characteristics that make them relevant to contemporary architecture and engineering.

• **Structural Stability, Integrity and Clarity**
  Tensegrity systems are self-stable and do not require external forces or anchor points to maintain their integrity. Shape is dependent on internal (material) and external (contextual) forces. In this sense, a tensegrity structure is literally a diagram of forces. Furthermore, discreet networks of tension and compression allow for a clear understanding of structural logic, behaviour and material appropriateness.

• **Material Efficiency**
  Buckminster Fuller believed that tensegrity structures are inherently materially and structurally efficient due to the slenderness of compressive elements and the primary use of tensile cables. Structural engineer B.B. Wang has theoretically demonstrated that this is true in some cases but not all (Wang 2004). Despite this, it is typically believed by architects and engineers that tensegrity structures exhibit a high strength to weight ratio and are thus interesting in terms of reducing material consumption and increasing structural efficiency.

• **System Scalability**
  The modular and self-contained nature of tensegrity systems means that they can be extended indefinitely to create larger frameworks suitable for architectural space making. Furthermore, they exhibit scale invariance and follow a self-similar fractal-like logic, meaning they can be nested within each other at numerous scales. This is demonstrated in Fullers original patent, and in H_edge (2006), a tensegrity project by ARUP Advanced Geometry Unit (AGU) in London under the direction of Cecil Balmond.

• **Fabrication Feasibility**
  Tensegrity structures can be constructed in a low-tech manner using simple materials. For example, timber dowel and elastic bands at model scale or bamboo and rope at architectural scale. Instead of being the only possible means of producing a design, CNC manufacturing simply widens the potential design spectrum of tensegrity structures.

• **Re-configurable**
  The discontinuous nature of compression elements and integral nature of tensional elements results in re-configurable structures that exist in a state of dynamic equilibrium (Hanaor 1992). By adjusting the length of tensile members, homogenous compressed elements can be used to construct an almost limitless number of heterogenous self-supporting structures.

• **Anisotropic Stiffness**
  The equilibrium state of a tensegrity structure depends not only on its topological characteristics (the manner in which elements are connected), but also on the elasticity and amount of pre-stress in the tensile members. The amount of pre-stress in turn governs flexibility. By modifying pretension either globally or locally, stiffness can be varied throughout a tensegrity configuration.
• **Integration of Structure and Ornament**
  Tensegrity systems are highly distilled force-driven forms that nevertheless hold a certain aesthetic appeal. Moline suggests that the H\_edge project mentioned earlier “reforges the functionalist design opposition between structure and ornament by making ornament instrumental” (Moline 2008: 1).

• **Uniform Distribution of Load**
  In tensegrity structures “all components are dynamically linked such that forces are translated instantly everywhere; a change in one part is reflected throughout” (Flemos 2007). This means that internal and external loads are uniformly distributed across structures rather than being resisted locally. This creates better integrity and allows material reduction.

**Brief History**

Research into tensegrity and its applications in architecture and engineering has a long history and many contributors. Renowned polymath Buckminster Fuller and artist Kenneth Snelson are commonly regarded as joint pioneers. Fuller coined the term, which appeared in his original patent (Fuller 1962). An examination of tensegrity related literature points to a previous independent discovery of the basic 3-strut tensegrity prism. Wroldsen (2007) and Gomez-Jauregi (2004) both provide an in-depth account of the origins, shedding light on its roots within the Russian Constructivist movement and tracing the earliest examples to the work of Latvian artist Karl Loganson from 1919 – 1921. French architect David Georges Emmerich (1925-1996) cited a structure by Loganson as a precedent to his own work (Burkhardt 2008). Kenneth Snelson also cites the Russian constructivists, of which Loganson was a member, as an inspiration for his work (Lalvani 1998).

Over the past six decades, there has been a significant amount of research into tensegrity structures. Motro (2002), Gomez-Jauregi (2004), Wroldson (2007), Burkhardt (2008) and Skelton (2009) each provide a detailed background and identify various applications in art, architecture, engineering & science.

**Principles and Definitions**

Within architecture and engineering circles, tensegrity structures are understood as a special case of prestressed systems (Skelton 2009). A prestressed structure is one whose overall integrity and stability depend on stressing parts of the structure prior to external loads being applied. Prestressing creates permanent stresses in a structure. It is generally implemented for the purpose of improving structural performance under various service conditions [Wikipedia Contributors 2011: np]. In tensegrity structures, tensile elements are pre-stressed such that internal forces are present in the system even when no external load is imposed.

The fundamental principles underpinning the tensegrity concept can be found in Fuller’s original patent *Tensile-Integrity Structures* (1962) where he describes a tensegrity structure as an assemblage of tension and compression components arranged in a discontinuous compression system (Fuller 1962). A more prosaic definition offered by Fuller is “a structural relationship principle in which structural shape is guaranteed by the finitely closed, comprehensively continuous, tensional behaviors of the system and not by the discontinuous and exclusively local compressional member behaviors” (Fuller 1975: 700.011).
Snelson submitted his own patent three years later titled *Continuous Tension, Discontinuous Compression Structures* (1965) and has also referred to tensegrity as the *floating compression* principle [Snelson 1990]. Snelson considers tensegrity to refer to “a closed structural system composed of a set of three or more elongate compression struts within a network of tension tendons, the combined parts mutually supportive in such a way that the struts do not touch one another, but press outwardly against nodal points in the tension network to form a firm, triangulated, prestressed, tension and compression unit” [Snelson 2013: np].

Artist Tom Flemons has suggested that “a tensegrity requires at minimum three conditions to fit either Kenneth Snelson’s or Buckminster Fuller’s definition” (Flemons 2007: np). According to him a tensegrity must firstly comprise of a continuous connective tensioned network supporting discontinuous compression struts. Secondly, they must be prestressed under tension, self-supporting and independent of gravity. Finally, Flemons proposes that tensegrities must be self-contained non-redundant whole systems. This third assertion can be observed in isolated Class 1 tensegrity systems but need not apply in all instances. One of the strengths of tensegrity systems from an engineering standpoint is that large modular arrangements include redundancies that permit local structural failure without compromising overall structural integrity.

Numerous definitions have been proposed for tensegrity, but they all vary according to the interests of their authors. Following is a small selection chosen for clarity and the capacity to cover the specific family of tensegrity structures developed during this investigation and described in more detail later.

- Anthony Pugh has offered a widely accepted general classification:
  
  A tensegrity system is established when a set of discontinuous compressive components interacts with a set of continuous tensile components to define a stable volume in space [Pugh 1976: 3]

- Rene Motro makes a distinction between patent-based and extended tensegrity structures:
  
  Patent-based definition:
  “Tensegrity systems are spatial reticulate systems in a state of selfstress. All their elements have a straight middle fibre and are of equivalent size. Tensioned elements have no rigidity in compression and constitute a continuous set. Compressed elements constitute a discontinuous set. Each node receives one and only one compressed element.” [Motro 2003: 19].

  Extended definition:
  “Tensegrity system is a system in a stable self-equilibrated state comprising a discontinuous set of compressed components inside a continuum of tensioned components” [Motro 2003: 19].

- Robert Skelton and his team offer a useful way of distinguishing between different taxonomic classes of tensegrity structures:

  A tensegrity configuration that has no contacts between its rigid bodies is a Class 1 tensegrity system, and a tensegrity system with as many as k rigid bodies in contact is a Class k tensegrity system [Skelton & de Oliveira 2006: 3]
Based significantly on work developed during my research, a definition for tensegrity structures that make use of 3D compression members is given by Zhou et al:

“\textit{The structure is composed of 3D compression members and tension network. The 3D members are discontinuous (not connected with each other). The whole system is stable, self-stressed and constructed using a set of discontinuous compressive components contained within a continuum of tension} [Zhou et al. 2011: 5894]"

There is no all-encompassing definition for the vast range of known and potential tensegrity structures. A general rule is that compression elements are discontinuous (do not touch) and interact with a continuous network of prestressed tension elements to form a stable volume in space. Tensile elements are generally called cables and typically compression elements are struts.

Motro’s dual definition enables a distinction to be made between two broad categorisations. The patent-based definition pertains strictly to class 1 structures where struts are linear and never touch. In contrast, Motro’s extended definition is similar to Pugh’s general classification. He expressly points out however, “\textit{the shape of the compressed component is not prescribed to be linear, surface or volume type: it can be a strut, a cable, a piece of membrane or an air volume}” [Motro 2002: 99].

Furthermore, Motro considers the word \textit{inside} as a key part of the extended definition since it differentiates tensegrities from typical structures where primary load bearing elements usually resist compression rather than tension. Motro’s extended definition specifically covers the novel structures presented in the following sections, as does the definition offered by Zhou et al.

**Obstacles for Design and Deployment**

While Kenneth Snelson has successfully exploited tensegrity principles to produce gravity defying artistic sculptures, in an issue of the Journal of the International Association for Shell and Spatial Structures devoted to tensegrity, Rene Motro makes it clear that even with thorough investigation by engineers and architects over the years, the ability to determine, control, visualize and deploy tensegrity structures within building and construction remains elusive (Motro 1992). Motro observes “\textit{there has not been much application of the tensegrity principle in the construction field}” [Motro 1992: 81] due to the fact that examples “\textit{have generally remained at the prototype state for lack of adequate technological design studies}” [Ibid].

In other words, despite their many promising qualities, tensegrity has so far proved challenging to implement within architecture. Burkhardt (2008: 34) outlines what he sees as the four primary obstacles to deploying tensegrity within building and construction:

1. \textit{Strut congestion} – as some designs become larger and the arc length of a strut decreases, the struts start running into each other.
2. \textit{Poor load response} – relatively high deflections as compared with conventional geometrically rigid structures.
3. \textit{Fabrication complexity} – tensegrity structures are complex which can lead to difficulties in fabrication.
4. \textit{Inadequate design tools} – lack of design and analysis techniques.
Initial Experimentation

Aware of these complexities and potential issues, I nonetheless embarked on an initial period of experimentation, which involved building a number of Class 1 tensegrity modules in simple materials such as straws, rubber bands and elastic (Figure C2a). It quickly became apparent that while these structures could potentially be aggregated to produce a skeletal architectural framework, their behavioural and fabrication complexity would indeed make them difficult to construct and control at building scale. Furthermore, while typical Class 1 and 2 tensegrity systems appear intriguing due to the counterintuitive nature of the discontinuous compression elements, I found that their appearance en masse was often not particularly elegant from a design perspective.

In mid 2008, these observations led to collaboration with engineers from the Innovative Structures Group (ISG) at RMIT University. Our collective aim was to explore the potential of tensegrity structures that utilise more advanced compressed assemblies. Our goal was to develop easier to control and construct tensegrity systems that would overcome some of the difficulties outlined by Burkhardt and could be successfully deployed at the scale of architecture and infrastructure.

In the next section, I describe this collaborative effort and present a novel class of tensegrity that makes use of three-dimensional compressed components.
C3 Compressed Component Development

3D Compressed Components

The majority of applied research into tensegrity has been situated in the realms of art and engineering rather than architecture. In most cases, including those where architects have been involved, the focus has been on class 1 and 2 tensegrity systems constructed from cables acting in tension and linear struts acting in compression. There are few practical examples where compressed elements consist of subassemblies that form more sophisticated geometries and even fewer that are relevant to architectural design.

One such example however is the classic ‘Double – X’ created by Kenneth Snelson (Figure C3a(ii)). This piece is formed using X-shaped timber elements and cables. A further example is Snelson and Fuller’s original ‘tensegrity mast’, which uses 3D compressed components made from spokes radiating from the gravitational centre of a tetrahedron to its vertices. A variety of theoretical examples can be found in the work of B.B. Wang, a Chinese engineer who has carried out extensive research into extended tensegrity structures. He calls these structures non-contiguous cable-strut systems [Wang and Li 2005]. Importantly, Wang concludes that such assemblies display increased structural efficiency compared with conventional tensegrity systems [Wang 2004].

Figure C3a illustrates the differences between a 1D strut, 2D X-shape and 3D tetrahedral tensegrity structure. Figure C3-1a(i) is a simple 3 strut per level tensegrity, Figure C3a(ii) is ‘Double-X’ constructed by Snelson in 1949 and Figure C3a(iii) depicts a tetrahedral member tensegrity mast similar to Snelson and Fuller’s, which I constructed using 3D printed components.

It is clear that the 2D X-shape and 3D tetrahedral pieces are resisting compressive forces in these models. The different configurations offer each tower differing degrees of geometric and mechanical freedom. The way each module connects to others determines how loads are transferred and the degree of variability that can be achieved. Adjusting the length of cables between modules consequently enables a wide variety of forms to be generated with a single tensegrity assembly.

Using 3D components in place of linear struts clearly restricts the kinematics of each tensegrity module. When modules are interconnected, restricted kinematics results in a more rigid, robust and controllable framework than conventional tensegrity assemblies. Moreover, 3D components significantly reduce strut congestion and fabrication complexity by minimizing the number of individual structural elements needed to induce a state of self-stress [Frumar et al 2009]. According to the principles and definitions outlined by Fuller, Snelson and others (Pugh 1976, Motro 2003, Skelton & de Oliveira 2006), a stable, self-stressed structure created by discontinuous three-dimensional compressed components within a continuous tensile network also satisfies the definition of tensegrity.

3D components can be freeform, symmetrical or eccentric in shape. The design potential of 3D compressed component tensegrity structures depends on the geometry of the compression subassembly, overall shape of the modules and in what manner the modules can be tessellated.
A 3D compressed component module suitable for use in architectural construction must satisfy the following requirements:

- Extreme vertices bound a closed volume
- 3D components are discontinuous when modules are interconnected
- Modules can tessellate in at least one direction

For a tensegrity module to be useful in architecture it needs to be able to span, frame and/or fill space. A module that can connect to other modules in a number of different directions will be of greater use to designers than one that can only extend in a single direction. A module that can generate self-similar (scale invariant) space-filling lattices would further enable design control and a higher degree of design potential.

Constructing 3D components from 2D pieces

To broaden the spectrum of design possibilities, three basic shapes – tetrahedron, octahedron and icosahedron – were chosen to serve as a basis for a series of 3D components. The reasoning behind this decision is that these three Platonic solids are fully triangulated, regularly proportioned and physically stable. Each shape became the basic framework for generating a series of compressed components. Principally, the components were developed by radiating spokes from the gravitational centres of each polyhedron to its respective vertices (Figure C3b).

The 3D components generated through this investigation were fabricated via 3D printing. For practical and economic reasons, three basic 2D laser cut pieces were further developed to enable quick and easy assembly of the modules. The 2D pieces can be described as: X-Shape, Linear bar and Tetrahedral angle (Figure C3c). These three planar geometries allow a variety of 3D module types to be rapidly assembled (Figure C3e). Their configuration is specified in Figure C3d.

6. More information on the geometric and mechanical principles of these fundamental shapes can be found in Levin 2006 and Scarr 2008.
Figure C3c Laser cut parts for 3D components based on stable polyhedra: X-piece, Linear bar, and tetrahedral angle

Figure C3d Configuration of 3D compression members

<table>
<thead>
<tr>
<th>Modules</th>
<th>Required pieces</th>
</tr>
</thead>
<tbody>
<tr>
<td>i. Tetrahedron</td>
<td>2 x tetrahedral angle</td>
</tr>
<tr>
<td>ii. Octahedron</td>
<td>Linear bar, X-piece</td>
</tr>
<tr>
<td>iii. Rectangular Prism</td>
<td>2 x X-piece</td>
</tr>
<tr>
<td>iv. Cube Prism</td>
<td>Linear bar, tetrahedral angle</td>
</tr>
<tr>
<td>v. Cuboctahedron</td>
<td>2 x X-piece, 2 x tetrahedral angle</td>
</tr>
</tbody>
</table>

Figure C3e 3D components assembled using 2D laser cut pieces

Figure C3f Tetrahedron module and component

Tetrahedron

The tetrahedral compression member is easily assembled for practical purposes using 2 tetrahedral angles connected perpendicular to each other and rotated 90 degrees. The resulting 3D compression member geometrically connects the tetrahedron’s gravitational centre and its four vertices as shown in Figure C3f.
This component has been explored in several examples. A seven level tensegrity mast was created as an initial investigation (Figure C3g). The design of the mast is based on Snelson and Fuller’s original design. Inelastic tension cables in both vertical and horizontal directions connect the tetrahedral modules, which are set axially one on top of the other. The horizontal cables are connected between the top vertices of each module and the bottom vertices of the module above. This specific vector driven relationship prevents the whole system from horizontal expansion. Vertical cables are then used to rigidify the structure. Thus a self-stressed system is created. The vertical cables in the tower structure were manually adjusted to produce a slight curve in two directions. Figure C3h depicts a similar model constructed using elastic tensile elements. It is clear from these two examples that varying the amount of prestress and adjusting the length of tension cables enables a wide variety of forms to be generated from a limited number of different module types.

The tetrahelix tube shown in Figure C3i illustrates how 3D compressed components can extend the spectrum of possible tensegrity constructions. The tube is constructed with self-stressed tetrahedron modules (all four vertices connected by prestressed tension elements). Each module is connected with four other modules midway along their edge as shown. Although this tesselation pattern can be represented clearly in a planar diagram, in a physical model internal tensile forces must be countered by attaching opposing edges to form a stable cylinder. In this arrangement tetrahedron modules form a counter-rotating set of spirals around a central axis. Any number of modules can be added to indefinitely enlarge the tube length and diameter.

A similar structure can be formed using the kite prism, which demonstrates that 3D compressed components can maintain their structural integrity in certain arrangements even when critical angles are significantly varied. The capacity to vary angles, proportions and lengths of compressed assemblies without disturbing structural integrity makes 3D compressed component tensegrity systems of interest to architects exploring the design potential of associative modelling tools coupled with digital fabrication technologies.
Cuboctahedron

The basic 2D pieces developed for creating the tetrahedral and octahedral compression members were found to generate a range of unexpected elements. One example is the cuboctahedral compression member, which is assembled using two X-shapes and two tetrahedral angles. The resulting 3D component geometrically connects the cuboctahedron centre and its twelve vertices as shown in Figure C3j. The cuboctahedron module proved itself useful as a node for a tensegrity frame system.

A tensegrity node was developed that allows a structural frame to expand in six directions. The three axis node is formed using a cuboctahedron and four tetrahedron modules. It can be extended in the XY plane using tetrahedron modules and in the Z-axis using rectangular prism modules as shown in Figure C3k. Although limited to six junctions, the flexible connective logic of the cuboctahedral node enables these junctions to be non-orthogonal. The potential of this system is revealed when we consider the shape transformation principles discovered earlier. Specifically, by adjusting the lengths of tension members, the orthogonal frame can be transformed into a variety of stable non-orthogonal configurations.
The Representational Divide

The assemblies presented thus far are basic examples that demonstrate the feasibility of tensegrity structures with 3D compressed components and hint at their architectural potential. Although limited, these physical investigations were invaluable for developing an understanding of how tensegrity structures with 3D components work and creating a bi-directional feedback loop between design and engineering teams. Through these explorations, it was observed that a wide variety of stable forms could be achieved with a limited number of unique modules by adjusting the lengths/prestress of tension members. Testing this in reality however, proves to be labour intensive and challenging. While basic structures composed of a small number of modules are best explored as physical models, once an assembly reaches a certain size and level of complexity it becomes impractical to build physically during explorative phases of design (Kilian 2006, Seebohm 2008, Weinand 2009, Fleischmann & Ahlquist 2009).

To address this issue, a digital modelling environment capable of handling large numbers of elements is needed. The difficulty however is that the form of a tensegrity structure depends not only on geometry but also on a balance of forces among self stressed members. In other words, they exist in a state of dynamic equilibrium through the coupling of geometry and force (Hanoar 1992). Generally speaking, force dependent geometries cannot be adequately described by the current generation of CAAD and CAE software (Burkhart 2008, Sterk 2007, Seebohm 2008, Weinand 2009).

This incongruence or ‘representational divide’, becomes a significant limitation to the design process and presents a problem when attempting to explore the suitability of tensegrity structures for contemporary architectural applications, particularly if one intends on deploying complex or novel configurations. To determine the correct shape of tensegrity assemblies within a computational environment, form finding procedures are necessary to “find a geometry compatible with at least one self-stress state” (Motro 2002: 100).

Existing Computational Approaches

In attempting to digitally model tensegrity structures, it becomes necessary to look beyond standard 3D modeling environments towards software that combines geometric logic with force-based parameters. As mentioned earlier, engineers, mathematicians and programmers have driven much of the research and discourse around tensegrity structures, including research into computational methods of form finding. However, the methods and algorithms that have been developed thus far by Motro, Tibet and Pellegrino, Skelton, Burkhardt and others, have not yet been fully integrated into design or engineering environments.

Needless to say, there are exceptionally limited computational tools available to designers wishing to explore the generative potential of tensegrity structures. Presently those that exist can be grouped into three broad categories:
Animation based simulation

Software for creating 3D animation and developing video games utilise sophisticated physics engines to simulate the behaviour and interaction of real-world forces and structures. By exploiting this aspect, one can induce a state of tensional integrity within geometric assemblages by connecting rigid bodies with springs. A series of experiments using 3ds Max demonstrated the feasibility of such an approach for finding the form of basic tensegrity structures [pics of my experimentation]. These investigations revealed that it is difficult and time-consuming to input initial geometry and to fluidly manipulate the various parameters that govern shape change. While such issues may be overcome with scripting or programming, the graphically oriented nature of the software also raises questions around the accuracy of the simulations. Sterk (Sterk 2007) and Payne (LIFT Architects) have carried out cursory research into tensegrity form finding with animation tools. Their investigations similarly reveal complexities with utilising these tools for tensegrity form finding.

Associative modelling

As mentioned earlier, the form of a tensegrity structure depends not only on its initial geometry but also on the balance of forces between self stressed members. Associative modeling environments typically do not have features to support this requirement, however it is possible to parametrically define the mechanical behavior of a single tensegrity module using a 'twist angle' (Liapi 2001). Propagating the module via a suitable connective logic can generate complex tessellations whose global form can be altered by adjusting local parameters. An example of this approach can be found in the work of Katherine Liapi, who has developed a parametric method to accurately determine the shape of double layer tensegrity grids (Liapi 2001; Liapi and Kim 2004) and helical tensegrity networks (Liapi 2009). Although promising, I believe these tools require further development to enable more fluid exploration of tensegrity assemblies.

Force-Density Method and Dynamic relaxation

The two most common computational techniques for finding the shape of load bearing surfaces and structures are the force-density method and dynamic relaxation technique (Schodek 2005: 53). Both are designed to minimize the forces present in a material system by optimising its shape. The optimum shape is the one that achieves equilibrium between the external loads and the internal forces in the surface with the least amount of material [ibid]. Both techniques can be applied to find the form of tensegrity systems. Typically these approaches are explored within engineering research groups. They are based on traditional methods of finite element analysis (FEA) and thus provide a high degree of accuracy. Fagerstrom (2009) demonstrates an approach to tensegrity design that integrates dynamic relaxation with associative modelling in Generative Components (GC). A further example of integrating FEA tools with design software is RhinoMembrane, a commercially available plug-in for finding the form of tensile membrane structures in Rhinoceros. The latest release (Version 1.22) implements a tensegrity form-finding algorithm based on the force density method.

7. An exception to this is the functionality provided by two recent plugins for Grasshopper/Rhinoceros - Kangaroo Physics (2010) & Karamba (2010) – discussed in more detail in chapter four.
Each of the computational techniques described enable tensegrity structures to be designed and tested in a virtual environment. However, while these tools may be suitable to determine the shape of known tensegrity configurations during later stages of design refinement, they do not support the fluid feedback loop necessary to properly explore the generative potential of tensegrity structures. Animation based simulation is perhaps the most accessible to designers but it is labour intensive and offers questionable results due to its graphical nature. The associative modelling of force-dependent structures is still at a preliminary stage of development and the FEA techniques are not specifically suited to the early stages of design as they involve deterministic processes that produce a single ‘optimal’ solution to a known set of constraints.

To faithfully reproduce the material and structural behaviour of tensegrity structures and properly support early design exploration, an ‘active’ computational approach is needed whereby global geometry can be transformed in real time by manipulating local connections between and within modules. Furthermore, structural feedback is required to determine which parts of the structure are in compression and tension, and to communicate whether a given assembly is stable and conforms to a state of tensional integrity.

In the next section I describe a way of achieving these goals by appropriating a technique from the computer graphics industry.
Particle Spring Systems: Interactive Form Finding

Particle-spring systems are widely used in computer graphics to produce visually accurate interactive animations. They have been used to model textiles, animals and soft tissues as well as different elastic behaviors such as anisotropy, heterogeneity, non linearity and incompressibility (Baudet et al 2007). A particle is a node element that contains information about mass. A spring is a linear element defined by two particles and can contain information about force or charge, resistance and elasticity as well as mass.

A particle-spring system is a collection of nodes in 3D space connected by springs. Generally, springs exert forces on particles according to Hooke’s law. External forces such as gravity, weight and friction can also be accounted for. As described earlier, research into the suitability of using particle-spring systems for architectural design has demonstrated effectiveness for interactively finding the form of tension structures (Killian and Ochsendorf 2005). The MIT study concludes that particle-spring systems are a particularly powerful way for architects to explore a synthesis of materiality, structure and form, as they provide a computationally lightweight method of simulation that complements the early design phase by supporting an intuitive approach to form ‘discovery’ 8.

In a publication just prior to his death, the late Dr. Thomas Seebohm describes three-dimensional tensegrity structures generated from two-dimensional ‘topologies’ using an obscure Java based applet named Struck (Seebohm 2008). Struck is a particle-spring based solver developed in 1998 by computer scientist Gerald De Jong specifically to visualise tensegrity assemblies and configurations (De Jong 1998).

Within Struck each spring is assigned a desired rest length; when the spring length is greater than the at rest length, the spring is in tension and particles are pulled towards each other. When the spring length is less than the at rest length, the spring is compressed and particles are forced away from each other. A number of tools based on similar principles exist and are available online 9. Like Struck, these interactive interfaces have been developed primarily for visualisation and education purposes.

A detailed description of the analytic method used by Struck could not be found, making Seebohm’s research important for elucidating some of the mathematical principles behind the interface. He notes, “the method used by Struck for form finding is related to the force density method ... but different in its iterative, computational solution” (Seebohm 2008). From close observation, Seebohm deduces that at each node the net force is calculated from the compressive and tensile forces in the struts and cables acting on [a particular] node and the node is then moved a distance in the direction of the net force, most likely in proportion to the magnitude of the force. The number of nodes that will be moved in one iteration or tick is variable. The tensile or compressive force in the struts and cables depends on how far they have been stretched or compressed, respectively, from their at rest length” (Seebohm 2008). Seebohm reasons that the equations behind Struck are equivalent to Hooke’s law and thus approximate “the linear stress-strain behaviour of metal rods and cables when not overstressed” (Ibid). He concludes that the behaviour of tensegrity assemblies in Struck corresponds to physical structures in which self-weight is negligible (Ibid). Struck is therefore sufficient to support early design exploration of physical tensegrity assemblies, however it is not sufficient for later phases of design refinement, analysis and documentation.

8. Alqhuist & Fleischman have also looked into the use of particle-spring systems for generating tension active cable-net structures in their combined masters project submitted to the Emergent Technologies and Design program at the Architectural Association in London 2009. They report on their findings in Fleischman & Alqhuist 2009.

9. For example: Sodaconstructor, Springs World 3D (built with processing), Springie and Springdance (no longer available).