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Plugin Practice: Recasting Modularity for Architects

A project submitted in fulfilment of the requirements for the degree of Doctor of Philosophy

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Nicholas Williams, December 2017

Abstract

Contemporary digital design practice is reframing a creative dialogue between design and making. Empowered by an increasingly seamless interface between data and material, the domain of the architect is expanding to engage diverse processes across design and fabrication. New practices of prototyping are emerging in which architects creatively extend opportunities for custom production, exploring relationships of form, material, fabrication, and aspects of performance.

This research is driven by project work spanning such a broad domain across design and fabrication, through which I have developed a series of prototypes. In these projects I have created, used and appropriated numerous tools and techniques. In this dissertation, I focus on the ways in which I engage with such a diverse toolset, addressing the workflows of projects in order to frame a modularity of process. This modularity operates across multiple scales, from simple functions to more complex systems, and to varying degrees, from discrete elements to fuzzier arrangements. It is not derived from formulas for design but is instead grounded in expertise and experience. It emerges in response to specific demands for resilience and flexibility and frames a practice in which we plug together diverse processes to enable design and prototyping for architecture.

The first contribution of this doctorate is to demonstrate a modularity of process and highlighting its role at multiple scales through a set of diagrams. Furthermore, I frame a series of implications of this modularity of process for architecture practice. Modularity is here more than just a means of organisation across design and fabrication. Nor is it employed to improve efficiency, as it is in some areas. Rather this modularity of process is important to enabling the generation and control differentiation, collaboration across fields of knowledge, and exploration of interdependent design criteria. These underpin a plugin practice in which designers can interrogate the ways we calibrate process and outcome, and create and reuse diverse forms of knowledge.

Acknowledgments

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Through the project work I discuss here, I recount the rich contributions of an array of collaborators. These projects are explicitly cross-disciplinary and it has been thoroughly rewarding to work alongside many individuals including Daniel Davis, Brady Peters, Alexander Pena de Leon, Jane Burry, Mark Burry, Sascha Bohnenberger, Xiaojun Qui, Pantea Alambeigi, Richard Blythe, Paul Minifie, Amaury Thomas, Kristof Crolla, Daniel Prohasky, Dharman Gersch and Chen Can Hui. The most serendipidous part of all is the ongoing collaboration with John Cherrey whose passion and is matched only by his skill. Such working relationships are rare.

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Definitions

Module

A distinct but interrelated part, a collection of which can create a system. Herein I address modules in design process in distinction to the material modules found in many building systems.

Workflow

A repeatable arrangement of process connected for a purpose. Herein I discuss workflows for design, using further terms to denote specific levels of detail.

Allographic

Scripted by their authors in order to be materially executed by others, as defined by Mario Carpo in *The Alphabet and the Algorithm.*

Autographic

Handmade by an author , as defined by Mario Carpo in *The Alphabet and the Algorithm.*

Abbreviations

AEC	Architecture, Engineering and Construction
CAD	Computer Aided Design
CAM	Computer Aided Manufacturing
CNC	Computer Numeric Control
NURBS	Non-Uniform Rational B-Spline
MC	Mass Customisation

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1. Introduction

1.1 New Perspectives in a Potent Milieu

"The revolution… is the ability to turn data into things and things into data"
– Neil Gerschenfeld, How to Make (Almost) Anything, 2012.

Fundamental shifts are today taking place in the ways that goods are designed, manufactured and used. Underlying these shifts, digital technology has become ubiquitous across many industries, from the media we use for communication, to the machines we use to make things. The term Industry 4.0 is now widely recognised, describing an industry with, "end to end digitization… and integration into digital ecosystems with value chain partners" (Vedsø et. al., 2016). Through this digital ecosystem, concepts from manufacturing such as mass-customisation and digital supply chains are increasingly relevant to many fields of design, including architecture.

In the midst of these broad shifts, digital fabrication has become a vital field. There is much evidence at hand, from research groups to start-up businesses and online communities. Perhaps the most significant example is the global network of over 700 FabLabs (Fig. 1.01). which have grown from a first iteration launched in downtown Boston in 2003. These labs now act as a global network to educate and to stimulate entrepreneurship in local communities (Gerschenfeld, 2012, 47).

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Figure. 1.01. Map showing locations of over 700 FabLabs of the global Fab Foundation.

This uptake of digital fabrication is significant among architects. Globally, Schools of Architecture now own suites of digital fabrication tools, with industrial robots sitting alongside off-the shelf 3D printers, CNC routers and other pieces of newly affordable digital kit. Conferences and peer-reviewed publications addressing digital fabrication for architects are also well established. Furthermore, major research initiatives in the field have been funded by governments and industry, highlighted by examples such as the National Competency Centre for Research in Digital Fabrication, established for “Switzerland to take a leading position within the global field of digital fabrication” (www.dfab.ch, Fig. 1.02). Architecture practices are also beginning to utilise digital fabrication to deliver challenging buildings. These design practices are connecting with leading fabricators and collaborating with other practices to enhance both the design and delivery of projects.

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Figure. 1.02. Stratafications installation by the Chair of Digital Fabrication (Gramazio Kohler), ETH Zurich, using robotics laser scanning and algorithms to assemble timber blocks, exhibited at the inaugural Fabricate conference, University College London.

The potential for architects lies not just in digital fabrication serving the delivery of design, but also in driving it. Through linking making with design, opportunities emerge across, “a creative and experimental process that occupies the full extent of architectural production” (Sheil and Glynn, 2012, 8). Today, connections between design and making are being engaged by a thriving community in practice and academia, creating new material systems, materialising non-standard forms, and exploring new fabrication techniques. A culture of prototyping is emerging which continuous design and evaluation drive innovation (Burry and Burry, 2016). This further engages fields beyond design, from structural design to acoustics and material science, among others.

While the relationships of design and making have long provided a rich milieu for architects, digital technologies provide, “a vast expansion on the remit, scope and potential of the designer” (Glynn and Sheil, 2011, p.156). This in turn creates significant challenges and opportunities to the way we practise design. We can harness knowledge across broad fields by connecting diverse collections of tools and techniques. In doing so, we must not lose a drive for novelty which compels designers, “to explore, to discover something new, rather than to return with yet another example of the already familiar” (Cross, 2006, 8). Here, architects must be more than just facilitators, acting as co-authors of systems and tools across multiple scales.

This research questions the ways we organise and integrate practice across this expanded domain. As we connect diverse tools and techniques, we must negotiate questions about how we constrain or enable design and make trade-offs between competing design drivers. The organisation of our workflows across design and fabrication bear significant influence on the outcomes of these workflows.

1.2 Motivation and Aim

From its outset, this research has been motivated by a series of perceived limitations in contemporary architecture practice. The first of these comes from my experience in commercial practice, where for over 10 years I have contributed to projects from individual houses to large institutional buildings. In this practice, a contingency for the architect was consistently evident – that of designing around pre-existing construction systems which could be priced, procured and installed by a builder. There is much room for creativity in such a role, but design is nevertheless constrained. For example, on an institutional building in Hobart, Tasmania, only one contractor was capable of fabricating the precast concrete façade panels. As such, this company set limitations as to what could and couldn't be built and how much they would cost, a role which was not just pragmatic but contractually accommodated. Such stories are common in contemporary practice.

Alongside this, in 2008 I was awarded scholarships to study in the Design Research Laboratory at the Architectural Association School of Architecture, London. My time there coincided with the start of the ProtoDesign research agenda in the course, a shift to engagement with making and fabrication. Here myself and classmates made numerous prototypes to connect digital models with material systems, most significantly through plaster poured into fabric (Fig. 1.03). This material "form finding" was both experimental, evocative, and with precedent in construction research (www.umanitoba.ca/faculties/architecture/facilities/cast.html). However, the reach and scope of these projects was limited, removed from the realities of delivering a building.

With skills in writing code and a desire to use these to deliver challenging buildings, I then took up a position at *DesignToProduction* in Zurich (designtoproduction.ch). Here I contributed to detailed fabrication models for some significant timber structures and was further exposed to working for someone with a computer science background. This taught me much about organising information and the abstract structures of software. Frustratingly, however, we were generally engaged only after the design phases, left to help resolve complex challenges created by others.

Figure. 1.03. Fabric and plaster study from the SoftCast project undertaken in the Design Research Laboratory, Architectural Association School of Architecture, designed and fabricated by team Anon, Mustafa el Sayed, Sara Saleh, Omrana Ahmed and myself, 2010.

These three perspectives – of an architect adapting a design to a specific set of construction resources, a designer using studio exercises to explore potential material systems for construction, and a fabrication consultant trying to resolve challenges created in early design stages – contributed to personal dissatisfaction around the ways we practise architecture. As such, this research is motivated by the belief that an integrated and expanded practice promised by digital fabrication remains unrealised in many situations today.

Furthermore, I seek to provide insights which are not formulas for design. Attempts to create and apply such rules sit awkwardly in the breadth of contemporary design practice, difficult to adapt to the specific constraints and opportunities of individual projects. They also run counter to fundamental aspirations of design practice to pursue the new and avant-garde (Hagan, 2008, 20) and to value difficulty over ease and efficiency (Willis and Woodward, 2010, 201). As a result, I pursue knowledge which is grounded in the pragmatic undertakings of practice and provides insights to our understandings of it.

1.3 Research-in-Action

Rather than pursue a conventional scientific research methodology, I here use a research-in-action methodology centred on a series of projects and the outcomes and reflections of these. This written component captures these reflections, produced to frame and contextualise the project work and subsequently to discuss implications of it. Unlike an approach which uses methodological conventions, project based research requires other heuristic methods including those from creative practice. This is an increasingly common model for research, with strong roots and a body of examples at RMIT University, and with significant uptake at Universities across Australia and internationally (www.architecture.rmit.edu.au/projects/adapt-r/).

Such a research-in-action methodology is underpinned by several key texts which highlight how knowledge is created through design. Peter Downton simply observes a principle of continuous learning through doing, asserting that designing is, “a way of producing knowledge for designing” (Downton, 2004, 56). Brian Lawson supports this idea of continuity, observing that a designer is “continually reflecting on the current understanding of the problem and the validity of the emerging solution or solutions” (1980, 299). Nigel Cross (2006) concurs that knowledge can be created through design, but challenges simple uncritical acceptance by highlighting the central importance of substantial reflection. Describing a designerly way of thinking, Cross asserts that by thinking through the objects created in design, re-useable knowledge can be gained and communicated, thus distinguishing a mode of research from conventional practice (2006, 102).

Further to highlighting that knowledge is created through design, this research methodology is particularly relevant to addressing questions about practice. Donald

Schon frames a reflection-in-action approach in which a researcher’s, “inquiry is not limited to a deliberation about means which depends on a prior agreement about ends. 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). This highlights an inherent interdependence between theory and practice, with the two developing alongside one another. While it is a problematic situation, as Schon describes it is nevertheless inherent to design. Through producing works of architecture, such as those discussed herein, we can inquire into challenges facing the practice of architecture.

This research centres on a body of project work and reflection upon this. Central to this is a series of major projects are presented in this dissertation. Each pursues a hypothesis about a specific relationship between the design of form, performance, material and fabrication. A prototype is realised in each, with a specific focus in the design and execution of a system to realise this. These projects each stand alone as a research inquiry though which knowledge is created. Recognition of this knowledge lies in the numerous exhibitions and peer-reviewed publications of the work. Beyond these core projects, I present a series of trajectories to discuss tools and techniques which relate to the original projects and have been applied elsewhere.

The contribution of this doctorate lies beyond the outcomes of the individual projects within it. Across the project material, I focus on the modularity of workflows. I demonstrate this modularity at multiple levels of detail and to varying degrees. Far from a trivial mapping of process, this turns out to be a necessary, though rarely addressed, aspect of practice. It is complementary to key design ambitions, from enabling us to manage complexity to enhancing how we collaborate. It further poses questions about how we calibrate our design process and use and share multiple types of knowledge.

1.4 Structure of this Dissertation

To provide critical context for the project work undertaken in this research, in Chapter 2 I address three key issues around the relationship of digital fabrication tools to architecture. Firstly, digital fabrication technologies have expanded the role and scope of the architect beyond established practices of design and documentation. The technology presents opportunities at the service of design, providing improved capacity for delivering complex and challenging projects. Furthermore, new practices are emerging which help link architecture, engineering and fabrication through digital services. There is now a broad community who are actively engaging and exploring fabrication, materials and broad notions of performance to drive design. This community is now looking beyond technological novelty to seek broader innovation in industry.

Recognising the drive for relevance in industry, I then discuss two parallel practices of prototyping in which architects address products and design. I outline a historic trajectory, beginning with early industrialised building and the enthusiasm of many avant-garde architects towards mass production (Smith and Timberlake, 2011, 3). This attitude stands in contrast to the gaps between many contemporary design communities and prefabricated building which exists today (Knapp, 2013). Alongside this prototyping for products is prototyping which drives design. This is finding a contemporary relevance as it enables forms of open innovation (Guggenheim, 2010) connecting diverse aspects of design and production. Falling between these two practices of prototyping are manufacturing trends which utilise increased means for customisation to explore new types of product.

The final background section addresses emerging workflows of architects in the context of a broadened set of tools and techniques. These workflows ground and enable process across design and production. I identify modularity as a key feature of process in other industries, one which has underpinned major changes over recent decades (Baldwin and Clarke, 2000). I highlight the roles of modularity in the electronics and software industries to provide a background to the study of design-led prototyping which ensues.

After framing key issues through the background material, in Chapter 3 I frame an overarching strategy across the project-led research. I introduce key drivers for each project including hypotheses around the relationships of form, material and performance, and specific hierarchies of customisation. To frame my interrogation of modularity, I also introduce a taxonomy covering levels of detail and ways in which modularity varies in degree. Finally, I introduce conventions which underpin a series of diagrams which run through the project chapters and illustrate the workflows and modularity within them.

In the subsequent chapters, I present and discuss the project material in detail. Three investigations (Chapters 4-6) cover the design and fabrication of full-scale prototypes: the FabPod, the Sound Bites Shell, and The Music Room. For each, a series of stories is used to describe key processes which are plugged together to create broader design systems. After outlining these aspects of systems, I then present an overview of each and discuss the large-scale prototypes which were produced. Following the three primary projects, I present a series of tools and techniques used in subsequent projects. These follow directly from the earlier prototypes and highlight the continuing development and interchangeability of workflow modules.

Looking across the breadth of project material, I reflect on modularity in workflows in Chapter 8. In the first instance, this is organised around the levels of detail which I introduced previously, discussing the degree of modularity at each and implications at each level. This feeds into a discussion around known benefits of modularity to consider how modularity can complement design practice. Citing examples from the project material, I discuss how modularity of workflow can enable differentiation, collaboration and exploration in architectural design. Finally, I consider some key issues of a 'plugin practice' which is underpinned by a modularity of workflows and which are emerging as important aspects in contemporary discourse.

2. Background

2.1 Expanding the Domain of Architecture: Reconnecting Design and Making

2.1.1 Architects Embrace DigiFab

The current groundswell of interest in digital fabrication among architects has been some time in the making. This year marks 20 since the completion of the Guggenheim Museum in Bilbao, a project which borrowed digital technology from the aerospace and automotive industries to use 3D digital models to connect between design and the fabrication of the steel structure and its cladding (Shelden, 2002). While this building was pioneering in its scale and ambition, the late 1990s also saw a number of emerging architectural practices begin to leverage access to computer numeric controlled (CNC) machines. SHoP Architects was established in New York in 1996 and, using a CNC router, completed the timber Dunescape installation, a commission for the PS1 pavilion at the Museum of Modern Art in 2000 (Fig. 2.01). Practitioners such as Mark Goulthorpe of Decoi Architects (1998) and the research group Sixteen* (makers) (Groak, 1996) were explicitly engaging digital and material media, and writing about emerging design implications.

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Figure. 2.01. Dunescape installation by SHoP Architect, New York, 2000.

Beyond the turn of the millennium, the community of architects trumpeting the virtues of digital fabrication had grown to include research groups and books. Nick Callicott of Sixteen* (makers) authored Computer Aided Manufacture in Architecture (2001), providing an overview of contemporary processes for CAM and tracing these to a historic lineage of Charles Babbage's mechanical *Difference Engines* of the early 19th century (Callicott, 2001, 11). In 2002, Branko Kolarevic brought together a number of key figures for a symposium at the University of Pennsylvania and the subsequent publication from this event, *Architecture in the Digital Age: Design and Manufacture* (2003) has become seminal in outlining a vision of both "a very different kind of architecture and… significant redefinition of the architect's role in the production of buildings".

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Figure 2.02. Honeycomb Morphologies installation, Emergent Technologies Program, Architectural Association, London, 2004

In the same period, funding in academia began to support digital fabrication within schools of architecture. In teaching programs such as the Emergent Technologies at the Architectural Association, London, course leaders Mike Weinstock, Achim Menges and Michael Hensel used relatively accessible machines such as laser-

cutters and powder-based 3D printers to fabricate pavilion-sized installations such as The Honeycomb Morphologies project (Fig. 2.02). At Ball State University, Kevin Klinger established *iMade: Institute for Digital Fabrication* in 2002 as a 'catalyst' to connect students with designers and the manufacturing industry (http://i-m-a-d-e.org/?page_id=115). Klinger also served as President of the Association of Computer-Aided Design in Architecture (ACADIA) between 2003-04 and helped shape the association's annual conference titled *Fabrication* (Beesley et. al, 2004). This framed the growing importance to the topic to the digital design community. In the following year at the ETH in Zurich, both the designtoproduction research group emerged within the CAAD chair, and a new Chair for Digital Fabrication (Gramazio Kohler) was established.

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Figure 2.03. Smithsonian Institute courtyard, Washington, 2004 - 2007, architects Foster and Partners.

Outside the digital design community, emerging manufacturing capability was simultaneously drawing interest from a broader architecture audience. Taking a prompt from Gehry Partners, larger practices including Foster and Partners helped to develop digital supply chains for major public buildings such as the Smithsonian Centre (Fig. 2.03). Emerging practitioners Stephen Kieran and James Timberlake received the inaugural Benjamin Latrobe Fellowship from the American Institute of Architects, using the funding to research emerging cultures of digital manufacturing in the aerospace and automotive industries. They authored *Refabricating Architecture: How Manufacturing Methodologies are poised to Transform Building Construction* (2004) advocating for the adoption of practices around aircraft assembly. This addressed an audience beyond those explicitly interested in the digital, making bold claims to a mainstream audience about future changes to the profession.

This brief overview covers but a few notable examples over a decade of burgeoning interest in digital fabrication. It seeks to illustrate a geographic breadth and a diversity of practitioners experimenting with new tools and techniques. This diversity highlights differing attitudes to the role of technology, some of which are addressed herein. A uniting feature, however, is that the belief that the changes taking place are revolutionary (Corser, 2010) with those involved broadly proclaiming that architecture would be turned on its head by new connections between design and making.

Moving forward to 2011 and the communities of architects engaged in digital fabrication have continued to grow, highlighted by the first Fabricate conference held at the Bartlett School of Architecture, London. Here, the works presented were separated into those undertaken within academia and those in practice, a division which was glossed over by conveners as "typical of but problematic to the discipline" (Glynn and Sheil, 2011, 20). Though problematic, this division frames two ways in which architects relate to digital fabrication. On one hand, fabrication is a subset of construction and largely independent of the design process. Here, digital tools such as CNC routers are valuable for improving the quality of prefabrication, and for realising complex forms, such as parts with unique angles and curved faces. This is at the service of design, harnessed to deliver a design intent. On the other hand, digital fabrication is central to design, used for exploring design opportunities. Here, fabrication drives design, actively shaping the design process and outcomes through mock-ups and prototypes.

The understanding of digital fabrication by architects continues to mature. The number of annual events and publications around the topic are growing, with new niches emerging around sub-topics such as robotics and materials. However,

distinctions between serving and driving design persist, with the technology transforming both "significant aspects of both design practice and delivery" (Corser, 2010, p.13). The two sides of this duality are teased out in the following sections to provide further depth across current research and practice.

2.1.2 Serving Design

> "In the world of hand-making that preceded the machine-made environment, imitation and visual similarity were the norm, replication and visual identicality were the exception. And in the digital world that is now rapidly overtaking the mechanical world, visual identicality is quickly becoming irrelevant."
>
> - Mario Carpo, The Alphabet and the Algorithm, 2011, 3

Architects have not taken up the technologies of digital fabrication in isolation. While the term 'digital fabrication' is popular amongst architects, the tools and techniques being referred to are more commonly situated within Computer Aided Manufacturing (CAM). CAM has major impacts in many industries, from automotive to aerospace to clothing and furniture, some of which are outlined further in section 2.2.2.

For architects, the potentials of CAM have come to be appreciated in combination with other emerging digital tools and techniques. Writing in 2004, shortly after the ACADIA Fabrication conference and the publication of *Refabricating Architecture*, Todd Woodward and Dan Willis identify the roles of parametric modelling and BIM to complement digital fabrication, claiming "these three techniques are poised to significantly alter" the professional practice of architecture (p.182). Today, these three are established in architectural discourse and practice to varying degrees and in various combinations.

Parametric tools are used in many industries for design and manufacturing and a suite of tools are being used by architects. Their potential is widely recognised and the term parametric has been used in many contexts and to many ends, including to denote emerging architectural style (Schumacher, 2008). I refer here to a narrower definition aligned to the technical workings of parametric models, those which are used to create a set of related outcomes defined by a set of parameters. Typically, architects use these to create geometry, though the parameters can relate to many aspects of material and performance. These models are underpinned by graphs of constraints, to which designers “add, erase, relate and repair”, with geometry solved through the graph (Woodbury, p.11). This allows for geometry to be flexible in relation to the parameters, in contrast to being explicitly drawn or modeled by a designer. A lineage of such parametric tools in CAD technology can be traced back to Ivan Sutherland’s 1963 exposition of the Sketchpad (Sutherland, 1963, 1).

For architects, parametric models and digital fabrication can complement each other well. Parametric models commonly produce collections of related but differentiated forms. Digital fabrication can provide an efficient and accurate means to materialise these. CNC machines respond to the data being fed to it, irrespective of whether it is repeated or different each time. Through using parametric tools, we use the variation in form to drive variation in machining programmes. This points to a synergy in which “CAM enables the production of parameterised individual parts for (almost) the cost of mass production” (Scheurer, 2007, p.1).

The second of the complementary technologies, BIM, has less straightforward relationships to fabrication. Centred on “accurate virtual models of a building” (Eastman et. al., 2008, 1) BIM reflects concepts and practices in other industries including automotive and aerospace design. Alongside geometry, these models can hold information on a broad range of aspects, from performance criteria, to specifications of material and fabrication. As such, BIM models can be considered parametric, and are ideally centred on highly structured databases of information (Kensek, 2014, xxvi). However, contemporary BIM practice falls short of an idealised position in which an entire project is defined by parametric components. There are many challenges to a continuous information flows across design and construction, and the prevailing sentiment is that BIM has not fulfilled its potential (Lau, 2016).

The related concept of integration from ‘file-to-factory’, promoted in many industries, has been often dismissed as irrelevant to the project-based construction industry (Scheurer, 2010, 91). In 2004, Scheurer established the company

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Figure 2.04. Construction image of the Centre Pompidou, Metz, France, Shigeru Ban Architects, digital fabrication consultants: designtoproduction

designtoproduction in response to these limitations, providing bespoke modelling services for challenging projects such as the Centre Pompidou, Metz (Fig. 2.04). They are not alone. A number of similar companies have emerged such as One:One in Germany (onetoone.net), Front Inc. in Hong Kong and North America (frontinc.com), and even in Australia (www.ar-ma.net). Much like Gehry Technologies, which spun off from Gehry Partners, these companies are offering services in parametric modeling and the management of detailed information for digital fabrication. They work for a range of clients, from architects to fabricators, and focus on high-budget projects seeking to exploit emerging fabrication offerings.

Alongside these small practices are those serving other aspects of design. For example, *Evolute* was established around the research of mathematician Helmut Pottman and specialises in geometry (evolute.at). ROB Technologies (rob-technologies.com) and Odico (odico.dk) help designers connect with robotic fabrication. While these have grown from research in universities, commercial practices have also developed expertise in parametric modeling and fabrication workflows. Among engineers, the likes of Thornton Tomasetti (www.thorntontomasetti.com) and Atelier One (www.atelierone.com), seek to differentiate themselves through digital knowhow. Furthermore, specialist fabrication companies such as façade contractors Seele (seele.com) and timber contractors Blumer Lehmann (timber-code.ch) provide consulting services alongside their CNC manufacture.

These companies are representative of a rich and growing ecosystem of practices serving challenging projects. They reflect emerging roles for three techniques discussed here, with parametric modeling, BIM and digital fabrication complementing one another. However, while these companies have links and backgrounds in architecture, they operate distinct from architectural practice. This division underscores the deep knowledge and significant effort demanded by parametric design, BIM and digital fabrication, which are major hurdles to them being used in early stages of design to drive process and shape outcomes in architecture.

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Figure 2.05. Robotic hot wire cutting of foam block in the Odico factory, Denmark.

2.1.3 Driving Design

"Tools cut materials which make form"

- Frank Barkow, Spielraum, 2014

We can now look back on several generations of digital design communities who have evoked the avant-garde. A spirit of experimentation within these communities has pushed limits beyond conventions of design and materialisation (Picon in Gramazio Kohler [eds.], 2014, p.59). Among a recent avant-garde, the scale of ambition is highlighted by exhibitions such as *Architectures Non-Standard* held in Paris in 2003-04, which explicit aimed to shift the discourse (Benjamin, 2010, 78). In her curatorial essay, Zeynap Mennan sets out a case for rejecting norms, eschewing stability for the unstable, and those in a state of constant becoming (2008, 172). Digital tools, she claims, are giving freedom to designers to follow intuition which "ensures a never-completed space of creativity and non-identical reproduction, releasing an infinity of possibilities" (Mennan, 2008, 181).

Among the avant garde proposals exhibited in 2003, Greg Lynn's Embryological House proposes serial variation in the form of houses. Greg Lynn is today regarded as a seminal figure in architectural design and describes that contemporary designers work with 'families' of components, defined through a set of rules and implemented through partial differential equations. Here, design at multiple scales is undertaken simultaneously, "the design of the many and the design of the one, at the same moment, is not only thinkable as a concept but can be instrumentalised" (2008, p.172). This is an evolution of ongoing relationship between part and whole. Such a focus on a series of related but differentiated elements is having broad impacts on many aspects of design culture. (Carpo, 2011, 10).

The Embryological House project was speculative and was not developed towards a built outcome, presented as a series of images and abstract models. In the decade subsequent to Architectures Non-Standard, many designers shifted attention to serial variation in building components, from structural elements to window systems, some of which I have discussed in the previous section. In design discourse, this is

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Figure 2.06. Models showing design variations in the Embryological House Project by Greg Lynn, www.cca.qc.ca/en/issues/4/origins-of-the-digital/5/embryological-house

again a rejection of emerging norms, here responding to the seemingly immaterial outputs of the digital. In the midst of this shift is a challenge to the primacy of form in design. Axel Killian asserts that “design exploration needs to move beyond the description of form” (2006, 27). He and others have highlighted opportunities for process to shape design outcomes, here using aspects of material, machining and assembly as design drivers which are more holistic than mere experiments in form.

To this end, Lisa Iwamoto identifies a collection of techniques “that reveal the design ingenuity that arises from digital fabrication” for projects, “whose method of making ultimately informs the design aesthetic” (2009, 4). The techniques – sectioning, folding, contouring and so on – are intentionally both literal and abstract tasks linked with creative concepts and targeted at architects. Aranda Lasch provides a similarly provocative taxonomy of techniques for designers, framed through the lens of machine tooling (2006, p.5). A further list of techniques is put forward by Barkow Leibinger. These are more directly connected to industrial processes – bending, casting, punching, welding – and are illustrated through commercial projects, including

buildings designed for the metalworking machine manufacturer Trumpf (2009, 3). These techniques and processes do not provide ready formulas for design but rather point to possibilities for processes of fabrication to precede form, thereby shaping the process of design and the thinking of the designer from concept stage. This close coupling of fabrication with design continues and is today exemplified by several notable research groups. Proponents have put forward terms to denote the integration across the divisions between material and digital, including the terms digital materiality (Gramazio Kohler, 2008) material computation (Menges, 2012) and digital craft (Oxman, 2007). The ambition of these designers and researchers is for a symbiotic relationship between making and design, an imaginary “unified design and fabrication process based on a series of conversations between men… and machines” (Picon, 2014, 59). This evokes older discussions in architecture around the relationships of man and machine explored by the likes of Gordon Pask (Haque, 2007, 54) and Nicholas Negroponte (1976).

In contemporary research, these ideas are predominantly explored through small projects in which physical prototypes are fabricated to test and prove design concepts. The *Gramazio Kohler Chair of Digital Fabrication (DFAB)* at the ETH, Zurich, has been a leader in this context. Using familiar and simple materials such as bricks and timber blanks, design is driven through assembly in novel arrangements and sequences. By developing rules to vary the angle and positioning of these parts when glued together, arrays of highly dynamic geometries are produced (examples: *Flexbrick, The Sequential Wall*). Alternatively, customised joint shapes can be cut into blanks to vary arrangement between components. (example: *The Catenary Pavilion*). In each case, the convergence of designer, machine and material provides new ground for design exploration.

At the *Institute of Computational Design (ICD)* in Stuttgart, emphasis is more explicitly placed on material. Again, research is primarily undertaken through a series of pavilions, each exploring a novel application of specific materials - timber and fibre composites (Fig. 2.07). Achim Menges describes the aspiration for “innate characteristics, behaviour and capacities of the material systems… to play a more active role in design computation” (2012, 36). Computation is framed here as a process occurring outside a digital computer but solved through material. This draws on the concepts of form-finding set out by Frei Otto and others in Stuttgart, seeking to extend such an approach using contemporary digital computers.

The work of the DFAB group in Zurich and the ICD in Stuttgart are two pertinent examples of digital fabrication being employed to help drive architectural design and design discourse in new directions. As with the previous section, this is not a comprehensive survey. Rather I seek to highlight key ideas, demonstrating that through addressing fabrication, design can tackle interactions with material and machines. Most significantly, this reaches beyond the disciplinary boundaries of architecture, regularly engaging with structural design, acoustics, and material sciences. This begins to highlight an expanded domain and remit for architects. Furthermore, driving design through fabrication raises aspects of performance in architecture, a topic I discuss more extensively in section 2.2 around practices of prototyping.

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Figure 2.07. ICD / ITKE Research Pavilion 2011, Stuttgart.
http://www.arch2o.com/wp-content/uploads/2012/04/223.jpg

2.1.4 Beyond Novelty

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Figure 2.08. Fabrication Hall in the Institute for Technology in Architecture (ITA) building, a key facility for the National Competency Center in Research – Digital Fabrication, ETH Zurich (www.dfab.ch/wp-content/uploads/2014/08/rfl.jpg)

Before moving on, however, I want to note that the dichotomy of serving and driving of design is not an easy distinction. There are, unsurprisingly, many crossovers of people and ideas. Bob Sheil describes “a creative dialogue” between design and making, with the potential to foster convergence (2012, 9). When looking across this community of designers interacting with digital fabrication, we can see many instances of design pushing the limits of fabrication, and fabrication providing fertile ground for design. In the project chapters here, I will highlight ways that fabrication both serves and drives design as two sides of such interdependent relationships.

Beyond close relationships, there is palpable anticipation that this is a major shift for architecture. Architects have long found connections between design and making, but this goes beyond previous examples of architects engaging with craft practice. Historian Mario Carpo claims a change in paradigm in practice, from an allographic to an autographic way of building. Carpo frames allography as prevalent in contemporary architecture and extending back to the seminal renaissance figure of Leon Battista Alberti (Carpo, 2011, 20). Here, design is codified through a consistent set of tools to denote geometry and scale (2011, 19), distinct from building. Through digital tools across design and fabrication, Carpo sees the reemergence of autographic practices and a potential to break centuries-old norms.

There is also evidence that the interest in digital fabrication, which only fifteen years earlier pursued novelty (Callicot, 2001), has now shifted to ambitions for broader innovation in industry, most immediately in the building industry. Investment is being made to drive this. For example, the *National Competency Center in Research – Digital Fabrication* in Switzerland is one of the largest examples of resources invested to "develop ground-breaking technologies for tomorrow's construction" (dfab.ch, Fig. 2.08). Other networks are similarly trying to link academia and industry, including the *Innochain Network* (innochain.net) and the *Digital Fabrication Network* (dfab.net). Large contracting firms such as Laing O'Rourke are also investing. These initiatives bring together experts from across disciplines and drive customised production. This ambition for innovation evokes older ambitions for architects to directly drive product innovation in the construction industry.

2.2 Practices of Prototyping: Shifting Ideas of Product and Performance

Amidst the current enthusiasm for digital fabrication, it is possible to overlook a long history of architects attempting to innovate on the building site. Architecture has long been a potent milieu in which to question industrial production. There are reciprocal influences between architects and the building industry which contribute to complex interactions of supply capability and market demand.

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Figure 2.09. Paradigms in Manufacturing, taken from Hu, 2013, p.4

A simple trajectory by Hu (Fig. 2.09) provides an overview of major manufacturing paradigms and concepts, charted through changes in the relationship of production volume and variety. Enabled by enlightenment principles of the division of labour and the development of mechanisation for key tasks, high-volume manufacturing began to flourish in early 19th century Britain. By 1890, leadership had shifted across the Atlantic as the 'American System' became dominant, employing improved management structures and production line techniques that enabled degrees of flexibility (Pine, 1999, 11). The increased production volumes not only serviced but created new markets, through the reach of products to service rapidly urbanizing populations. More recently, high volume has come to be complemented by higher levels of variety. So-called mass-customisation and personalisation have become dominant themes with a drive for customised products.

2.2.1 Prototyping for Industry

"Prefabrication architecture is a tale of necessity and desire"

– Smith and Timberlake, 2011, 3

Ryan Smith and James Timberlake outline a history of industrialised building (2011) which gained significant scale with the industrial revolutions in Britain and the US. By the early 20th century, models of mass production were making significant inroads into housing markets. Prefabricated kit homes found good market volume in the United States and as enthusiasm grew, prefabricated housing became, "a core theme of modernist architectural discourse and experiment, born from the union of architecture and industry" (Begdoll, 2008, 12). This was an ambition driven by recognised pioneers such as Le Corbusier who rallied architects to "create the mass production spirit... the spirit of conceiving mass-production houses" (1931,62). Underlying this was a modernist notion of prototype for products. This prototyping was necessarily outside of markets, preceding products they served. In the same period, at the newly established Bauhaus attention focused in mass production for household products. Architect and founder Walter Gropius promoted the Bauhaus studios as "laboratories in which prototypes of products suitable for mass production and typical of our time are carefully developed and constantly improved" (1975, 1). The designers being trained were to act as collaborators equally adept in form and technology.

However, at the scale of buildings, this modernist notion does not easily fit with a history of false-starts and failures (Knapp, 2013). Some failures have become relatively famous, for example Thomas Edison's *Single Pour House* in which concrete was poured into a formwork for a literally monolithic house. Edison's full-scale prototypes were compromised by material issues in both the moulds and concrete. More broadly, the proposal was undermined by a lack of demand for an entirely concrete house (www.flyingmoose.org/truthfic/edison.html). Alongside bold failures such as this are more nuanced examples, including many ideas that appeared destined for success. The Packaged House System (Fig 2.10), for example, teamed visionary architect (Walter Gropius) with master technician (Konrad Wachsmann) and industrial partner (the Industrial Panel Company) around a system of panels which could be

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Figure 2.10. Prototypes for mass-produced housing which found limited success. Thomas Edison's Single Pour House (patent 1908); Sectional drawing for the Packaged House System by Walter Gropius and Konrad Wachsmann (1942); The Loblolly House by Kieran Timberlake Architects (2006).

flat-packed for transport and assembled with a patented four-way connection system. Despite the quality and brand, commercial failure followed, put down to both bad timing and marketing, with refinements to the production system delaying launch, and government subsidies withdrawn in this period. (Smith and Timberlake, 45).

Today, the prefabrication industry is centred on Fordist mass-production (Smith and Timberlake, 18). The influence of architecture in shaping this industry have been significant though somewhat indirect. There are relatively few examples of architects creating successful product systems. However, alongside the seminal names already mentioned, the likes of Mies van der Rohe and Lloyd Wright had clear influence on driving modernist aesthetics. These were highly relevant to the means of industrial production in the mid-20th century. Further examples such as Buckminster Fuller's Dymaxion House, Jean Prouve's sheet-metal systems, and the Case Study houses commissioned in California from 1945-64, had influence on both systems of manufacture and on architecture (Smith and Timberlake, 26). These individuals, while recognised as innovators, did not achieve significant commercial success through products for housing.

Amidst this modernist period is another historic development of similar significance to contemporary practice, around numeric control (NC) technologies. Beginning from the middle of the 19th century, NC sought "to abstract properties into numbers in order to regularize, routinize and quantify that which is otherwise irregular, aleatory, and qualitative" (Moe, 2010, 154). US Military Ordinance took on these principles in the 1930s, and by the 1950s NC was being used not only to automate tasks but entire manufacturing processes, thereby driving both production efficiency and quality. Electronic control of machines was enabled through motors first developed by the Servomechanics Laboratory at MIT (Moe, 2010, 160) and were used by industry to exploit opportunities for market share (Callicot, 2001, 50).

The abstraction and standardisation that drove NC was manifest in modular, repetitive building systems. As the size of buildings demands the assembly of multiple components, repetitive and standardised modules of parts and assemblies became

synonymous with prefabricated systems. Early examples developed around cores for building services and grew to the scale of whole houses and larger building types. The drivers of cost and risk were clear "building in modules considerably reduces the overhead and onsite labour and can dramatically reduce initial cost" (Smith and Timberlake, 2011, 16).

The issues of cost and risk remain dominant forces in today's prefabrication industry. However, as design and construction are commonly separate tasks, the cost and risk-drivers of different parties also differ. There are nowadays pronounced gaps between the products of industrial prefabrication and that which architects design (Knapp, 2013). The latter is often highly bespoke and today architects play only minor roles in industrial prefabrication. In some contexts, this gap is widening.

2.2.2 Prototyping for Design

> "Prototyping is not simply understood as the development of 'first forms' or 'first strikes' as beta-versions of products as in industrial design, but as a more general mode of doing culture: a mode that is tentative, based on bricolage, user involvement and ongoing change and improvements of products and practices, as 'open innovation', rather than an expert in a closed lab who turns out a finished product to be used by an unknowing user."
>
> – Michael Guggenheim, The Long History of Prototypes, 2010

Many contemporary architects are framing prototyping as an essential element of their design practice. This is a cultural phenomenon broader than architecture, as highlighted by Michael Guggenheim's quote. This centres on a desire to overcome the divergence of design practice and industry, however, the ambition for this practice lies beyond simply driving new products. Contemporary prototyping aids the representation of complex formal and spatial ideas, which are themselves enabled and fetishized through digital technologies in forums such as Architectures Non-Standard. It is also a key aspect of framing performance within design discourse, connecting empirical testing of material artefacts with digital models and simulations. As architects address issues across a broad array of disciplines – aesthetic, structural, acoustic and beyond – so prototyping simultaneously tests and interrogates multiple issues and specific contexts. This goes beyond conventions of representation which are familiar to architects, providing persistent sites to question design ideas and intent (Ayres, 2012). Furthermore, prototyping can enhance design exploration by creating unexpected outcomes and events from novel combinations of material and fabrication process (Burry and Burry, 2016).

These issues underpin paradigms in which prototypes can act as progenitors for further design iterations (Burry and Burry, 2016) and as archetypes, established models for design driving subsequent decisions and further design exploration (Burry M., 2012, 73). The relationship between prototype and product is blurred as the outcomes of design process themselves act as tools for design. In this frame, the work of two historic figures, Antoni Gaudi and Frei Otto, are revered for their relevance to contemporary digital practice. Each created analogue computers to drive design through prototypes.

Realising that the ambitious plans for the Temple Sagrada Família in Barcelona could not be completed within his lifetime, Gaudi designed and prototyped systems to describe the organic geometries of the basilica. These centred on families of ruled surface geometries (Burry, 2007), with forms responding to issues including fabrication, acoustics and structure, several of which are further expanded in subsequent project chapters herein. The use of geometric rules rather than fixed forms is generative, and these have come to be regarded as key forerunners of contemporary parametric models (Burry, 2011).

Gaudi made further notable contributions through 'hanging chain models' to define funicular forms in response to structural loading of the cathedral (ref.). These used weights hung from networks of chains to simulate loading from gravity, albeit upside down. Through adjustments in loading, the form of the network of chains changes. More than 50 years after Gaud's death, Frei Otto directed the recreation of these models at his Institute for Lightweight Structures in Stuttgart (Tomlow, 1989). Otto extended the principles of these models to forge a broader field of 'form-finding', in which form is calculated through material models responding to loads, to the design of

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Figure 2.11. Models for form-finding (from top) Hanging Chain model of Antoni Gaudi; Design model for the roof structure of the Munich Olympic Stadium by Frei Otto, a contemporary digital model and representation in McNeel *Rhinoceros*.

numerous lightweight structures and develop formal languages which derive shape from material performance. These are sophisticated parametric schema, computing results of interdependent constraints to design form (Killian, 2006, 8).

Alongside a blurring of tool and product is also a blurring of tool users and makers. Where commentators on digital practice once sought to distinguish between the two (Davis, D., 2013, 26), more recently this distinction has been questioned as architects embrace a range of platforms to write software code themselves. Architects are using scripting languages to create bespoke digital tools for productivity, problem solving and design exploration (Burry, 2011, 38). In the latter context, scripting languages provided an important outlet for designers of many disciplines to not only define forms but to generate them (Reas & McWilliams, 2010, 17). The hanging chain models of Gaudi and Otto have become a key example of such transition to code libraries. These analogue prototypes have been digitised, firstly by academics in structural design (Williams, 2001) and subsequently for design exploration with architects (Killian and Ochsendorf, 2006).

In rapid fashion, this digital tools being created by design communities have evolved from a fragmented array of individuals into well connected communities sharing tools made for key platforms. This is exemplified by the open-source community around McNeel Grasshopper, a visual programming platform with a rich ecosystem of components which can be combined graphically, with “no knowledge of programming or scripting” (Rutten, http://www.grasshopper3d.com/). The hanging chain model is again a poignant example, with the physics simulation plugin, Kangaroo, providing simulations of these and other phenomena, with stable and fast code (www.kangraoo3D.com). This plugin is being regularly developed by Daniel Piker and applied to a plethora of projects by a global community of designers.

This lineage from Gaudi to Otto to contemporary practice highlights ways in which computation can cross digital and analogue media. Today’s designers now have access to a toolset which is sophisticated but constantly evolving, suitable for modelling complex systems from material deformation to simulations of natural phenomena.

Further, this exemplifies a practice of prototyping which provide continuous drivers for design. While the community is a small cross-section of broader practitioners and academics, it is having increasing influence not only among architects but also in other disciplines such as structural engineering (Adriaenssens et. al., 2014, XII).

2.2.3 Both Volume and Variation

“Customers are treated individually as in the customized markets of preindustrial economies”
– Stan Davis, *Future Perfect*, 1987, p.XX

While digital fabrication is driving change within architecture, outside the discipline digital technologies are contributing to major shifts across industry. A new paradigm is emerging, with digitised assets and processes underpinning so-called Industry 4.0 (PwC, 2016). Demand is becoming increasingly diversified, and distinctions between products and services increasingly blurred in supply, in particular within innovation-centred industries (McKinsey, 7). Here I touch upon just a few key concepts of this paradigm, focussing on customisation and relationships to currents practice of architecture.

The more recent shift towards customisation has been propelled by means to better tailor products to the needs and desires of customers. The term mass-customisation (MC) was first coined by Stan Davis in Future Perfect (1987) and gained more significant attention through business literature such as B. Joseph Pine’s book Mass-Customization: A New Frontier in Business Competition (1993). Nowadays it is a broad field, recognised as an important concept across contemporary business sectors (Da Silvera et.al, 2001; Fogliatto et.al., 2012). It is commonly understood in distinction with the standardised and repetitive output of 20th century mass-production.

MC is nowadays applied to varying degrees across most industries. Academic literature is dominated by research into strategies for technology and management structures to meet this (Piroozfar and Piller, 2011, 54). Much of this highlights the importance of digital technologies as enablers, “the technology and systems to deliver goods and services that meet individual customers’ needs with near mass production efficiency” (Jiao and Tseng, 2000, 225). At its core, customisation is enabled by standardisation and numeric control, the same technologies which were instrumental to mass production as discussed in section 2.2.1. Here, however, MC is utilised by production systems which manage and exploit detailed and vast information flows describing variation within these systems.

The design and development of mass-customised products nowadays leans heavily on modular systems spanning design and production. These systems involve a continuous balancing between the internal simplicity of a production chain and the external variety of product offerings (Jiao and Tseng, 2000, 226). Concepts such as ‘product families’ and ‘product platforms’ are nowadays well established (Simpson et.al., 2006, 3), and both top-down and bottom-up strategies are apparent in their design (Shapiro, 1998, 1). The former centres on the grouping of pre-existing parts and processes, based on shared aspects of production (Anzanello in Fogliato & da Silveira [eds.], 2011, 291) and levels of commonality between products (Jiao, J. and Tseng, M., 2000, 228). The latter centres on the structuring and design of systems for new product systems. The core of a product family provides a structure around which variation can be incorporated. By making product systems modular, elements from a product feature to a specific supplier can be varied or exchanged.

Architects first engaged with the terms and concepts around MC in the 1990s and the term is nowadays often used by those advocating for design prototypes in which numerous, unique components are fabricated (Maxwell et.al, 2013, 312). While this understanding overlooks many cost aspects in a commercial manufacturing chain, the implications of broader productions systems are highlighted in the first book dedicated to MC in the architecture and construction industries (Piroozfar and Piller, 2013). Many concepts associated with MC are familiar to architects. For example, ‘just-in-time’ production describes the production of parts in response to a specific order, an increasingly common feature in the construction of complex buildings (Scheurer, 2008, 63). Strategies to customise products late in production, so-called ‘form postponement’ and ‘time postponement strategies’ (Wong and Naim in Fogliato & da Silveira [eds.], 2011, 305) are also well understood though not explicitly recognised. Architects commonly engage with form postponement when specifying products such as

windows, which are most often different shapes and sizes, fabricated from a common set of extrusions (Willis and Woodward, 2010, 197). Designing within the constraints of such product systems is now common though architects rarely have insight into details of the manufacture process.

2.2.4 Beyond Technology

While many architects are exploiting the flexibility increasingly afforded through customisation in industry, some see it as imperative that the design and production are even more closely linked. Frank Piller and Poorang Piroozfar identify a series of increasing and competing pressures on construction, with improved performance and functionality encountering increased demands on cost (2013, i). They frame emerging paradigms of mass customisation and personalisation as indispensable. Others look further to advocate for bringing together the two practices of prototyping in industry product and in design practice (Burry M. and Burry J., 2017, 8). To date, the impact on industry of experimental, design-led prototyping is tentative, with enthusiastic rhetoric tempered by warnings that these tools and techniques have not been tested at large scales (Verebes, 2014, 128). Long-term advocates are questioning the promise of design and digital fabrication to drive revolutionary change (Corser, 2010, 11).

Meanwhile, building product systems are designed and prototyped in an industrial context dominated by cost and building codes. This is the domain of industrial designers, a practice which is normalised but stands in contrast to the modernist ambitions of the likes of Le Corbusier, and the aspirations of today’s design community which has engaged fabrication and recently shifted its focus to innovation in industry. Navigating this gulf between experimental practice and industry requires significantly greater connection across the parallel practices of prototyping discussed here.

To date, the common ground between these practices of prototyping in industrial products and for design practice has centred on technology. However, the perceived value of these technologies differs significantly. Industry sees value in efficient and flexible supply, with products that can be tailored to customer needs. For designers on the other hand, digital technologies offer means to rapidly materialise ideas in a continuous process of development and with relatively low demands on skill. A number of commentators urge design practitioners to look beyond these simple opportunities. Kiel Moe asserts that "in architecture, digital fabrication technologies will not change building production without fundamental shifts in the social and market structures of design practice" (2010, 164). He points to broader histories of technology, citing historian David Noble who highlights the shortcomings of a 'machine mentality' which frames technology as capable of answering major problems (Moe, 2010, 162). In *Building Systems* (2012), Moe and Ryan Smith cite Lewis Mumford's concept of 'technics' to outline the historic primacy of cultural over technical concerns. Antoine Picon (2005) supports this hierarchy, describing that the history of construction is largely removed from the history of technology, with construction innovation influenced as much by cultural questions.

Looking beyond technology to unpick the organisation and practice of design holds many challenges. As described above, contemporary practices of prototyping for design can blur relationships of tool and product, and of tool-makers and users. Furthermore, in section 2.1, I highlighted the increased breadth of engagement enabled by digital technology, crossing established disciplinary boundaries of engineering, business, materials science and more. Transdisciplinary design is not easily embraced by architecture communities who fetishize individual designers. Furthermore, designers tend to resist formulas which might streamline process but constrain design. Indeed, Willis and Woodward (2010, 201) argue that difficulty is itself a source of design value, and that making design easier or more streamlined is not desirable.

Though broad answers are beyond a PhD such as this, the unfulfilled promise of an integrated practice across design and fabrication is a primary motivation for this research. To this end, I now shift from framing a broad contemporary context to address process across these fields. The broad notion of process is grounded in the workflows composed of tangible functions and information flows across fields of knowledge.

2.3 Designing Workflows

Process is a broad topic with different emphases and patterns in different contexts. In manufacturing, for example, production process is centred on supply chains and largely disconnected from design. Linear flows of materials and information (Fig. 2.11) are common tropes, though the realities of contemporary industry nowadays commonly defies this through more complex information flow.

In contrast to this linearity, discussion of process in architectural discourse includes many aspects of design. This captures a diverse range of activities, including many idiosyncratic traits of individual architects. As I have discussed previously, computation can complement design intuition, though details of these digital design processes are rarely quantified. I have also described that architects are addressing an expanded domain across design and prototyping. Workflows are increasingly important for these shifts in practice, providing tangible and reusable structures which underpin information flows and design exploration. Here I discuss some features of these workflows for architects and relate key concepts around modularity which are broadly recognised and used in other fields.

2.3.1 Emerging Workflows and Platforms

> "New digital capacities are restructuring the organization and hierarchy of design from autonomous processes to collective workflows."
> – Scott Marble, *Digital Workflows in Architecture*, 2013, p. 7

It is an old adage that an architect needs "not to know everything, but to know enough" (Davis and Peters, 2013, 131). In the context of a breadth of contemporary digital technologies this is not only apparent but recast, requiring architects to have more than just disciplinary knowledge about design and construction, and more than mere management skills. With the increased scope and remit of design comes an increased imperative for design collaboration and multiple layers of design. Independent of a specific project, a designer might create a tool, be it a script or plugin, which is then applied and adapted by others (Carpo, 2011, 126).

To this end, contemporary design communities are congregating around key digital platforms. These include proprietary software packages, but are exemplified by more open platforms such as *McNeel Grasshopper*, a visual programming environment providing access to the NURBS geometry and functionality of its host program *Rhinoceros*. Through making itself extensible, *Grasshopper* has fostered a critical community across disciplines including architecture, structural engineering, environmental modeling and jewelery design. This community has created a vast ecosystem of plugins, developed and extended by individual contributors who share and support each other's work.

Davis and Peters borrow terms from the open source software movement to describe such open platforms as a 'bazaar' in which the "collective action of individuals contributes to the larger community" (2013, 126). This is placed in opposition to monolithic 'cathedrals', software programs which are developed internally by a large vendor. Such established software programs are being usurped by these platforms for sharing, and the design communities who create and share tools on them. Their maturity is highlighted by the use of such tools on commercial projects.

These platforms and communities highlight that designers co-author not only design outcomes but also systems and workflows for design. Smith and Timberlake borrow terms from computer science to describe that designers need both 'architectural knowledge', related to the overall structure and relationships of a system, and 'component knowledge' of specific elements of a system (2011, 337).

Addressing patterns of design, Axel Killian (2006) highlights that design exploration involves types of exploration which contrast linear flows elsewhere. Through research spanning multiple models and media he identifies circular, branching and parallel information flows. These patterns are in turn essential to establishing, refining and exercising constraints which drive relationships and underpin constraints within systems (2006, 3). That there are multiple and non-linear patterns will not surprise many designers, though such quantified representations of workflow are rare.

Scott Marble (2013) provides a more in-depth study of workflows. This aims to take discussions of process from a relative autonomous actions of individuals to the workflows which operate across them (p.8). The book addresses workflows across three themes within the AEC industry. Most immediately relevant to an architecture audience is the designing of design, a task which must negotiate the technical and cultural imperatives of design (Marble, 2013, 8). Beyond this, Marble addresses the design of assembly to interrogate workflows in an emerging construction paradigm of prefabricated elements which are assembled on site. Finally, Marble addresses the design of industry, framing both the influence and dependence of workflow upon the ways the AEC industry organises itself.

Marble's book is a relatively rare attempt to capture and quantify workflows. It brings together contributions from both practitioners and academics including many already discussed here including Barkow and Leibinger, and fabrication consultants such as Fabian Scheurer from designtoproduction. From this broad set of contributors come a varied array of diagrams as these contributors attempt to communicate the relationships of the many tools and techniques they have used across a diverse set of projects.

Workflows are at the centre of this research and the perspectives brought together by Marble provide an important base. In this research, I add to this base by addressing a lack of understanding of the ways we creating and reuse a diversity of tools and techniques. In doing this I frame a modularity of process in these workflows, considering their breakdown of parts and relationships at multiple scales. I illustrate this through a consistent approach to diagramming across a series of projects. Though not directly discussed, modularity is implicit in many of the contributions in Marble's book, apparent through the attempts to denote parts of the workflows, through boxes and circles in diagrams. As I highlight in the following section, modularity is critical in many contexts and has been discussed to varying degrees elsewhere.

2.3.3 The Power of Modularity

"1. Rule of Modularity: Write simple parts connected by clean interfaces."
– Basics of the Unix Philosophy

Architects have long been urged to look to other disciplines to shape design. The automotive and aerospace industries have been highlighted as having similar size and complexity of product (Kieran and Timberlake, 2003, xi), and software engineering is more recently being framed as providing models for design (Davis, D., 2013, 5). As we turn attention to the workflows and process in achitecture, we can also draw from process in these industries.

Standard and repetitive material components remain at the core of most products, from consumer electronics to household goods. In contemporary industry, however, modularity is discussed beyond products to the processes of design and delivery which underpin them. The popularising voice of Mass Customisation, B. Joseph Pine II, asserts, "you must modularize your capabilities. Take your offering… and break it apart into modular elements." (2011, 2). I have already touched on increasing customisation in products, and modularity is a central strategy for this, through top-down design of systems and bottom-up interrelating of existing parts and processes (Simpson et. al, 2006, 6). Modularity allows externally developed technologies to be implemented and for product families to develop specific aspects from one generation to the next without starting from scratch (Meyer and Utterback, 1992, 1).

The significance of modularity has been articulated through key texts over the past two decades. Perhaps the most widely acknowledged is the work of Carliss Baldwin and Kim Clark. They penned *Design Rules: The Power of Modularity* (2006) to frame the development of the computer industry from the middle of the 20th century. They describe a modularity which is interconnected and nested. This modularity crosses scales (2006, 123) and operates across critical aspects of production, from the engineering design, to the people who implement and maintain the design and the economic system around it. More broadly addressing engineering systems, they frame three key benefits of modularity: "to make complexity manageable; to enable parallel work; and to accommodate future uncertainty" (2004, 1).

Alongside such a perspective addressing broad scales of industry, are firsthand reflections from the software development community. Despite the promise of computation, in the 1970s a major crisis occurred in the software industry as the complexity of large development teams limited the software that could be realised (Davis, 2012, 51). Overcoming this required a reorganisation of the industry. The adage of modules which do "one thing and do it well" is framed as primary building block in the *Basics of the Unix Philosophy*, which was distributed to the open source community of developers to help reduce debugging time and simultaneously unlocking potentials for parallel work. Importantly, this philosophy is "pragmatic and grounded in experience" rather than the result of misplaced idealism (http://homepage.cs.uri.edu/~thenry/resources/unix_art/ch01s06.html).

Furthermore, modularity is an important consideration in modeling complex systems, from economies to climates. These require the interaction of experts from many independent fields of knowledge. The establishment of modular systems with consistent interfaces between them is an important to success. Bursting simplistic ideals of clean models, Eric Winsberg and Johannes Lenhard (2010, 261) highlight a "fuzzy modularity" in such systems, referring to climate models as a key example. Despite attempts to structure these models with clean structures and interfaces, there is inevitably a degree of "kludging" required to calibrate parts of the system and achieve a meaningful veracity in results. This fuzziness points to variability in degree of modularity, as system parts differ in their levels of internal cohesion and external clarity. The study of the degree of modularity has grown over the past decade, including to address engineering systems (Hölttä-Otto and de Weck, 2007).

While many parallels have been drawn between process in architecture and in other fields, it is somewhat surprising that modularity of process has received little explicit discussion among architects. The practice I address here entails the design of systems to explore and prototype architecture. These systems connect digital models and material systems as architects confront an increased scope and remit in design. This research interrogates the modularity of these systems for design, addressing both the scale and degree of it.

3. Research Strategy

3.1 Overview of Project Work

In the previous chapter I have framed a contemporary context of architects using digital fabrication. This includes those using digital fabrication to both serve and drive design, the latter exploring interdependencies of form, material, fabrication and performance. I have also discussed practices of prototyping as they relate to both volume production and bespoke outcomes centred on design. Finally, I have discussed workflows in architecture and introduced the concept of modularity as it relates to other fields. Each of the elements here are central to this dissertation.

I now turn to the project work of this research. This is undertaken as a strategy of reflection-in-action, involving iterative design, fabrication and reflections upon outcomes. This strategy is championed by authors such as Schon (2004) and seeks to rigorously extend current design knowledge through both critically engaging the state-of-the-art and creatively challenging and extending it by exploring new territory to reframe the contexts and grounds for argument. This is especially relevant to research such as this which engages technologies that are relatively new to architecture.

A number of prototype works of architecture have been created through these projects. These are first and foremost design prototypes, created through design exploration for testing ideas, gaining insight into the progress of experiments and for refining and recalibrating further experiments (Burry and Burry, 2016). These prototypes also hold simple aspirations of driving products, pointing to potentials for combining such design practices with industry.

The focus of this research is on the processes spanning design, fabrication and assembly of these prototypes. This covers a diverse array of tools and techniques, exemplified by the combination of acoustic simulations alongside the setting of bandsaw blades, and studies of geometric intersections of hyperboloids alongside scripts to automate the generation of CNC machine files. These combinations enable exploration of specific hypotheses and are necessary to specific outcomes. They go beyond ad-hoc experiments to be refined and resolved through iterative testing into robust workflows.

3.1.1 Design Systems and Trajectories

The project material of this research is organised into four parts. The first three of these each address a project to create a full-scale piece of architecture. Each of these built works is considered a prototype and the workflow designed and created for it termed a design system. The fourth part addresses design trajectories, following the development of specific tools and techniques through further project-based research. These trajectories address finer levels of detail than the broad design systems.

Through the project work of this research I have inevitably engaged with a vast array of various types of system. I use the term Design System to describe project specific workflows. They run across many other systems from a diverse field. Kiel Moe and Ryan Smith (2012) highlight the multiple systems, ranging from the tangible building systems employed for elements such as facades, to the more abstract and immaterial systems of society and culture with which design engages. Alongside this are the so-called material systems being created and interrogated through contemporary practitioners such as Achim Menges (www.achimmenges.net/?page_id=18298).

These design systems do not draw distinction between processes engaging digital and material media and tools. They regularly connect information related to digital models with data from digital simulations and physical tests, to information for fabrication and assembly. In a broad context, this agnosticism towards medium leans on Neil Gershenfeld's explication of the physical laws which underpin electronic information technologies, with bits manifest as atoms (2006).

3.1.2 Research Hypotheses, Drivers and Technologies

In the background chapters, I elucidated two parallel conditions in contemporary architectural discourse, those of design serving and driving design, and practices of prototyping addressing production and design. These are regularly returned to as themes throughout the project chapters. Within these, a number of further designerly ambitions are apparent. They include differentiation at multiple scales, the exploration of relationships between interdependent design drivers, and collaboration across disciplines. These are deeply ingrained through all of the project work herein.

To interrogate these themes and ambitions, I set up the major prototypes here to simultaneously address three forms of research driver (Table 3.01). In the first place, the research for each is underpinned by a hypothesis around interdependent relationship of geometry, material, fabrication and performance. These draw on theory from both within and outside architectural discourse, relating architecture with acoustics, structural design, robotics and materials science. Through these hyptheses, we can creatively question attitudes to the ways we design and measure performance in architecture.

The system which is created for each prototype is also framed by a primary affordance. This frames the ways in which each system provides flexibility and constraint in the design of part and whole. Finally, the production of each prototypes involves a specific digital fabrication technology. The ability to design across these technologies helps highlight challenges and opportunities of designing for specific machines at the delivery end of projects.

Project	**Hypothesis on form, performance & material**	**Primary Affordance**	**Fabrication Technology**
FabPod	That hyperboloid geometries are excellent for generat-ing acoustically diffuse spaces.	A system of customisation in both part and whole.	5-axis CNC router.
Sound Bites	That an optimal structure is provided by a specific shell form responding to load cases.	A system of shared design models.	3-axis CNC router.
Music Room	That robotic fabrication can enable the fabrication of customised and novel components.	A system which is driven by a novel and robust fabrication technique.	6-axis robot on a linear track.

Table 3.01 Key propositions used to form research hypotheses for investigation.

Three primary design trajectories emerge from these primary prototypes. These are tools and techniques which are adapted and developed for further project work. They further highlight the breadth of activity which a body of project work like this can cover, and the many possibilities which are created through it.

3.1.3 Interfacing Diverse Parts

The prototypes in this research are of a select scale, large enough to produce habitable spaces (up to a floor area of 100 sq.m.) yet sufficiently small for a researcher like myself to have detailed input across them. However, the research demanded I engage design beyond the disciplinary bounds of architecture. It further demanded that I engage with quantitative performance to an extent well beyond the heuristic design knowledge of an architect.

To meet these demands I assembled and worked with teams of individuals with expertise across many fields. I was a leader and key decision maker in each, instigating specific conversations to build relationships, explore design opportunities and realise prototypes. The members of each team are named in each of the project chapters, and I further discuss key collaborations with individuals. The nature of these collaborations varies greatly, from longer term relationships developed over multiple projects to brief interactions, often at a distance.

Alongside the need to interface with many people is a need to link information related to a diverse array of machines and material parts. I address a diverse set of tools and techniques throughout the project material and I frame the interfaces between these as information between process steps. These interfaces are composed of specific information, the output of one process becoming an input to subsequent processes. Designing and implementing these interfaces is a key aspect of the 'plugin practice' being addressed here.

3.2 Framing a Modularity of Process

I have already touched upon some basics of how process is understood in various fields, including contrasts between fields like manufacturing and design. Rather than appropriate the structures of any of these fields, in this research I develop an approach which draws on several key precedents. To communicate this approach, I create diagrams to describe multiple scales degrees of modularity in workflow.

3.2.1 Degrees of Modularity

It is overly simplistic to consider modularity as a discrete and binary condition. As I have already highlighted, examples such as complex digital simulations of climate models require a fuzzy modularity to relate and calibrate parts of a system (Lenhard and Winsberg, 2010, 261). In their seminal text *Design Rules*, Baldwin and Clark admit that "clearly there are degrees of connection, there are graduations of modularity" (2000, 63). In software and engineering systems, there are numerous metrics to measure the degrees of internal coupling and the interrelationships between modules within a system. Baldwin and Clark admit, however, that in many systems simple metrics for modularity break down.

In the design workflows presented here, modularity varies in degree. Quantifying these variations with strict or objective metrics is difficult given the diverse processes related through a complex array of factors. For example, while relationships in parametric schema can be readily quantified, translating this digital information to a fabrication process such as routing involves a range of parameters such as tool speed and material finish. These are themselves difficult to measure and are dependent on further details such as local imperfections in the material. It would be near impossible and somewhat irrelevant to drill down through every arrangement within the systems here. As a result, the degree of modularity is more simply measured and represented here on a linear scale. This measure ranges from a low degree with little cohesion and reliability, to highly robust elements which provide consistent results. This allows us to understand aspects relative to one another.

3.2.2 Levels of Detail

Alongside considerations of the degree of modularity are multiple levels of detail within workflows. These can be more easily distinguished and I draw on the PhD research of John Everett (1991). Everett's research addresses potentials for robotic automation of construction processes and he identifies levels ranging from the broad organisation of the construction industry to orthopedic of individual actions, outlining types process and significant information at each level. As with my research, these levels span digital and material domains, as Everett addresses digital machinery and the automation of material processes, such as excavation. As such I appropriate these levels as a starting point for describing levels of detail in this research.

Of particular relevance are five levels of details within Everett's taxonomy, running from the level of a Project to that of Elemental Motion. In appropriating these levels I have adapted names to suit specific concepts being addressed by this research. The new terms are compared to Everett's taxonomy in Figure 3.01. Further to this, I briefly characterise and frame each of the five levels of detail below, listing a series of examples relevant to each. These are provided to assist in understanding each level and its relationship to digital tools and material.

Design System

A system created and used in pursuing a a single generation of an architectural prototype. This is equivalent to Project in Everett's taxonomy, here renamed to highlight that all entities are specifically related and could be reused for further prototypes.
Examples: Entire workflows for the FabPod, Sound Bites and Music Room prototypes.

Division

Major areas of work within a Design System, commonly divided by conventional discipline and related to the expertise and leadership of key people.
Examples: Architectural Design, Structural Design, Acoustic design, Fabrication Design, Form Finding.

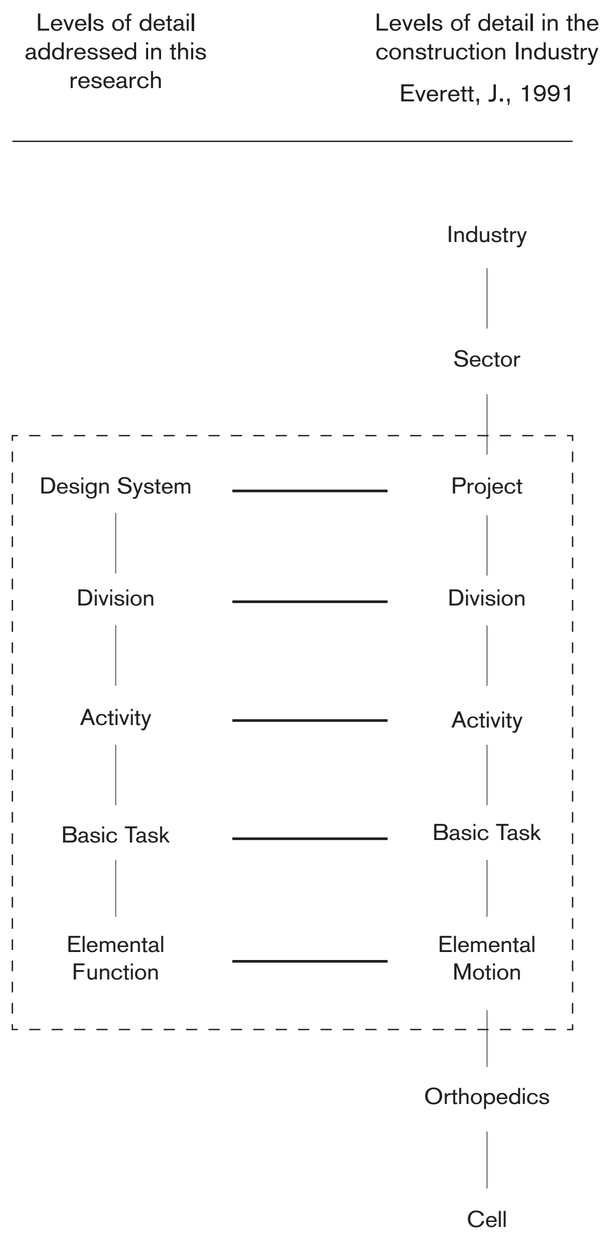

Figure 3.01. The scales of detail for design systems compared to Everett's levels of detail in construction.

Activity

Primary and broad processes which require significant effort and expertise.
Examples: Calculating reverberation time, simulating structural deflections, setting a bandsaw blade, defining a robot toolpath, vacuum forming plastic, flank cutting in a sheet material, glue-laminating timber, routing holes at specific coordinates.

Basic Task

Elements of work requiring multiple inputs but in themselves relatively straightforward. These combine multiple Elemental Functions for more significant outcomes.
Examples: Calculating a geodesic curve, discretising a NURBS curve, moving an object through space along a given trajectory, planing a piece of timber, applying glue to a surface, picking up a Blank from Cradle.

Elemental Function

Basic motions and processes requiring simple and few inputs. The can be readily achieved without significant skill, preparation or research. While they can theoretically be further broken down, they stand along and produce consistent results.
Examples: offsetting a curve, lofting a surface, intersecting NURBS surfaces, setting the feedrate for a router, setting spindle speed for a router, drilling a hole, opening a glue bottle, actuating a pneumatic clamp.

At the finest end of this scale, the Elemental Functions, we have a series of robust and reliable processes underpinning higher levels of detail. In his structure, Everett cites studies relating human motion to time units (p.71) thereby providing a reliable basis which can be applied and undertaken in specific time periods. Here, I draw explicit parallels between such elemental motions and functional blocks of executable computer code. Functions in libraries of computer code can be similarly applied and executed in discrete time periods. These tweo types of process underpin Elemental Functions and provide a base from which to build more complex processes.

The most coarse level of detail, the Design System, is easily identified around

a specific piece of project work. Those addressed here are intentionally open with little internal connection. This allows for the design teams to respond to unforeseen issues, including pragmatic requirements of specific sites. As such, these systems contrast other systems which are highly resolved to ensure reliable and predictable outcomes.

3.2.3 Conventions of Diagrams

Throughout the project chapters that follow, a series of diagrams are used to describe the modularity of workflows. As with many fields, documenting these design systems in diagrams is largely a retrospective task. As Axel Killian notes, such diagrams, “require time to be created as well as insight into the process that may only develop during the exploration. Unfortunately, the diagramming process is unlikely to keep up with the associative brainstorming of designers” (2006, p.314). This does not diminish the significance of modularity but rather highlights that it is practised before it is recognised through reflection. It further highlights the interaction of both top-down and bottom-up forces in the genesis of the research.

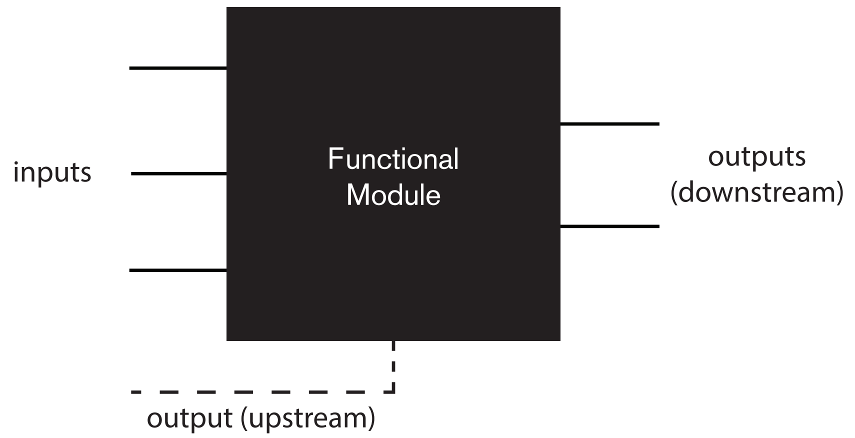

Figure 3.02. Typical workflow module with inputs and outputs and typical left to right flow. The darkness of the indicates degree of modularity, black showing high degree.

To create a system of notation which is consistently applied across the project material, the diagrams here follow a series of conventions:

- Workflow elements are represented through squares (Fig. 3.02). These have a size to indicate their level of detail, such as Function, Task, Activity and so on as listed above.
- Each element is coloured with a shade of black to represent its degree of modularity, black being a complete module and light grey with little modularity.
- As the workflows operate across multiple levels of detail, workflow modules are nested in larger modules (Fig 3.03).
- To represent information flow, elements are linked by lines to describe specific relationships within the systems. Solid lines indicate information flow downstream and dashed lines show upstream information flow for feedback. These lines show linear chains of workflow and others that branch and converge through parallel blocks of process.

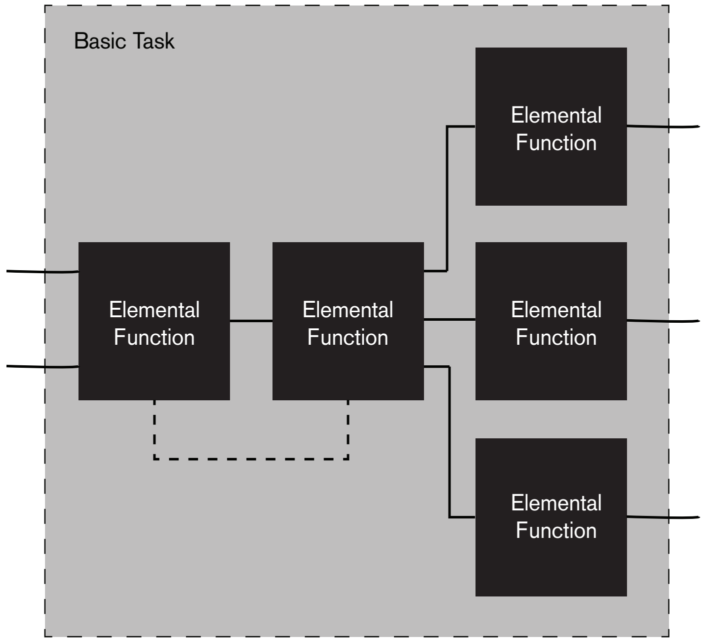

Figure 3.03. Typical arrangements across scales, showing a Basic Task composed of multiple Elemental Functions. The broader scale has a lower degree of modularity than the finer.

A final consideration in the diagrams here is to indicate the ways we reuse and re-purpose process. Throughout this research, we have used tools and techniques which were created outside this work. A reuse occurs in all black-boxed elements and from a level of Functions to more complex Tasks and Activites which are blackboxed. I have not indicated any particular feature of these as they are generic to all the workflows here. Some of these, however, have used tools created by others. Where this has occurred, I have indicated this through the use of a cyan coloured border (Fig. 3.04, left). Within any module with such a border, all process scales use that tool.

I further re-purpose processes created within earlier project work within this research. Where this has occurred, I have indicated so using a red coloured border and red shading to indicate the degree of modularity in that process (Fig. 3.04, right). This is particularly apparent in the FabPod project in Chapter 7.

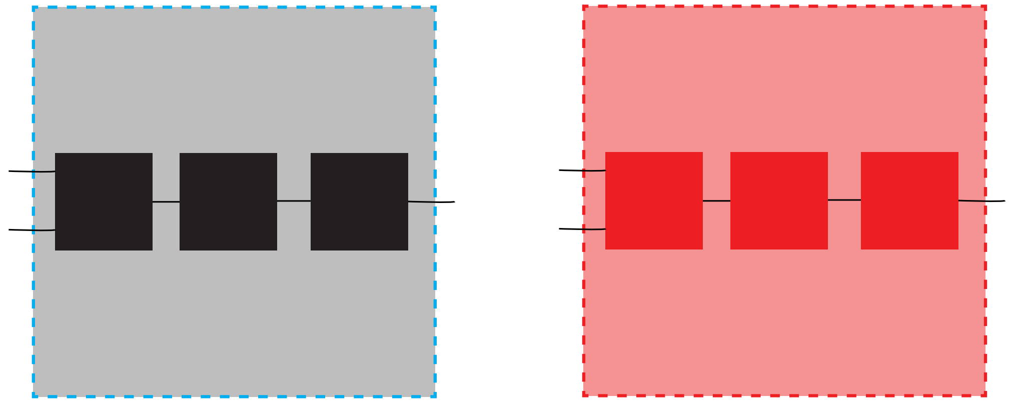

Figure 3.04. Process which has reused the specific functionality of a tool created by other (left) and process which is re-purposed from an earlier state within this research.

FAB POD

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4.1 FabPod Background

4.1.1 Research Premise: Acoustic Performance of Hyperboloids

> "We do not know if Gaudi had completed any in depth study of the acoustics of this church, but he was well aware that its structure, full of columns, pierced arches, broken volumes, and corners, was an effective way to avoid resonance. Furthermore, the hyperbolic paraboloid vaults disperse sound instead of concentrating it. We also believe, on the basis of our own experience, that such an internal structure avoids, to a great extent, the echoing that could be produced in the absence of extensive enough absorbent surfaces."
>
> - Puig I Boada quoted in Mark Burry, 2013, 118

The FabPod extends a line of research addressing the performance of hyperboloid geometries in scattering sound, and being employed to create acoustically diffuse spaces. This hypothesis draws on evidence from Antoni Gaudí's Sagrada Basilica (Fig. 4.01), the completed interior of which is lined with these forms. While there is no direct evidence that Gaudi understood details of specific acoustic properties of such forms, Puig I Boada, who studied under Gaudi and went on to direct the basilica project, attests to Gaud's awareness of how these forms might sound (Burry, M., 2013, 118).

The interior of the Sagrada Família is lined with several families of ruled geometries, including circular hyperboloids in prominent locations. These forms can be described as a hyperbola curve rotated around a single axis (Fig. 4.02). In a workshop titled Responsive Acoustic Surfaces (RAS) run at the SmartGeometry event in Copenhagen in 2011, a research team set out to explore the acoustic performance of circular hyperboloids. The FabPod which I discuss here extends directly from this research using circular hyperboloids.

The RAS research team used two, parallel prototyping approaches in their workshop. Firstly, they created patterns by distributing in a series of arrangements in digital models and then printing these in plaster at scale 1:10. Using a reverberation chamber, they then measured the scattering coefficients of these forms (Peters, 2010). Alongside these tests at scale, the team built two cylindrical walls in order to

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Fig. 4.01. Circular hyperboloid forms along the ceiling of the Temple Sagrada Família, Barcelona.

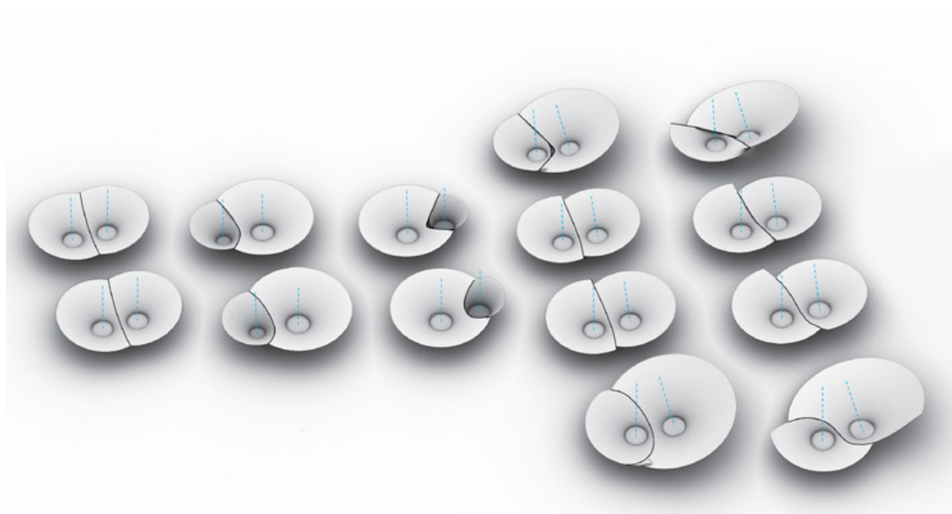

Fig. 4.02. Intersections of circular hyperboloid surfaces.

demonstrate the acoustic difference first-hand (Fig. 4.03). One of these walls was clad in plasterboard, the other with plaster components in hyperboloid forms. These hyperboloid forms were mounted on timber frames for stacking. When built, the team could readily hear the differing acoustics of each wall, with the plasterboard surface reflecting one's voice in specific locations, echoes which were not apparent in the wall of stacked hyperboloids (Burry, J. et. al., 2011).

The experiments from the RAS cluster provided a basis for testing and demonstrating sound diffusion with hyperboloid forms. Drawing on these scaled tests, Brady Peters (2010) demonstrated that sound scattering can be controlled using the geometric properties of the surface, in particular the width and depth of features. For the FabPod, we assembled a team including several original collaborators from RAS and set out to explore forms with aperiodic arrangements of circular hyperboloids.

4.1.2 Functional Brief: A Semi-Private Space for Communication

Open-plan office spaces have been promoted as good for team environments, providing spatial and visual connection between individuals and informal interaction, chance encounters between individuals. Not surprisingly, however, there are drawbacks to these open environments including a lack of acoustic privacy and spaces for small groups to meet (Machner, 2011). The FabPod commission addresses such situations, providing enclosures which are not closed rooms but which provide excellent internal acoustics and good separation from their surrounds. It simply called for a space that could comfortably seat up to eight people. Complete acoustic privacy was not required but rather the enclosure was to provide a good barrier to sound transmission, combined with an internal acoustic that was conducive to small meetings.

Presenting an immediate opportunity for an installation, the Design Hub building at RMIT University was nearing completion without an agreed solution for meeting spaces within the large 'warehouses' of the building. A suitable commercially available product was not identified, and the client provided support to design and build a research prototype.

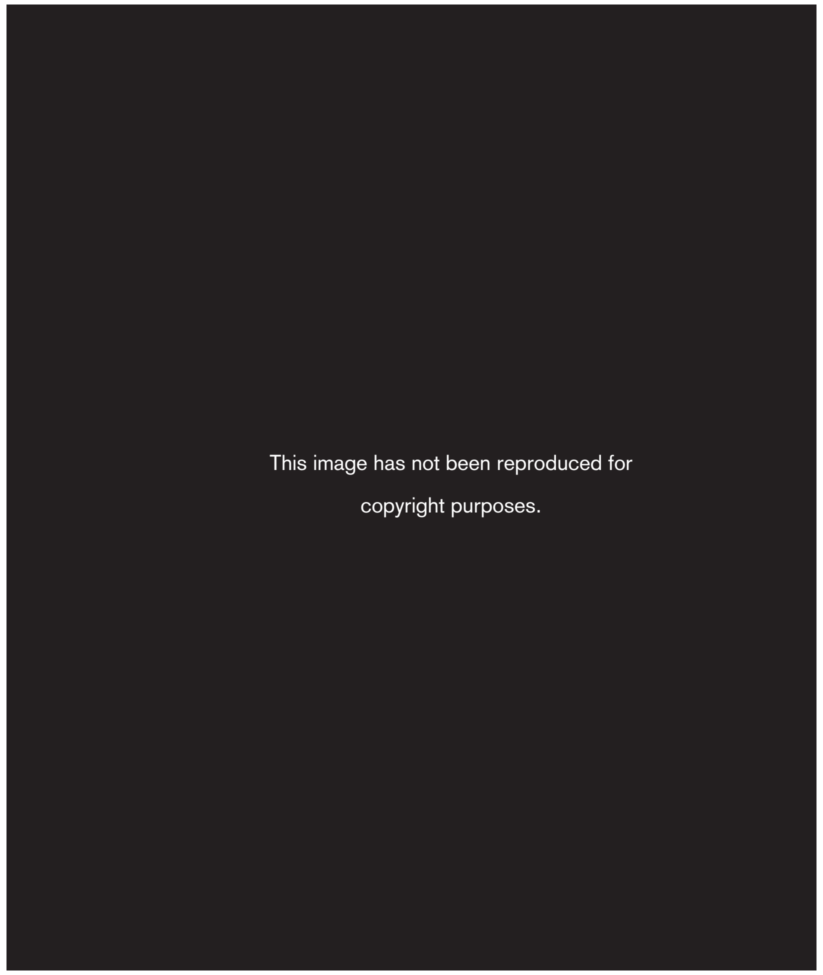

Fig. 4.03. Two cylindrical walls built in RAS workshop, one sheeted with platerboard and the one articulated with with hyperboloids.

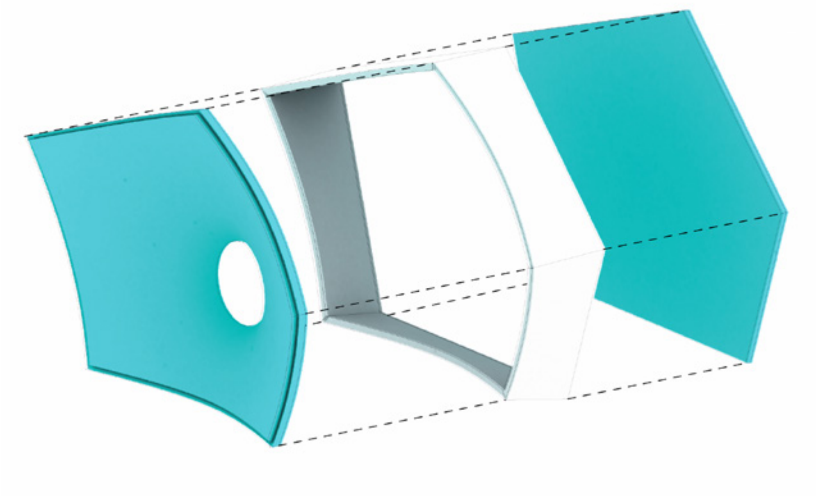

Fig. 4.04. Basic arrangement of a parts in a 'cell' for the FabPod - a hyperboloid and a flat face mounted on a timber frame.

We identified from academic research that the FabPod should provide some sound reduction close to the source, good speech intelligibility without loud and quiet spots, and a space that would sound bright and lively rather than be deadened by too much absorption (Bradley, 2009). To achieve this, we recognised that the interior surfaces of the enclosure should combine partial acoustic absorption alongside harder materials which scatter sound. We also identified that by deploying absorptive materials and forms on the outside of the structure, we could also improve the auditory experience of the surrounding workspace (Petersen, 2008).

4.1.3 Prototype Focus: A System for Customisation at Two Scales

I led initial conversations with the team in which we identified features and limitations from the earlier prototype which could drive this next iteration, including:

- An interior space enclosed by hyperboloid forms on enclosing walls
- Hyperboloid faces mounted on a frame as prefabricated, stacked components
- Limited control and challenges to finishing hyperboloid forms made with plaster
- Poor geometric intersections between hyperboloid components, traced to geometric problems by component and overall wall form.
- Challenges in fabricating bespoke frames using 3-axis laser-cutting.

These background conversations highlighted a desire for customisation at the scales of both component and overall form of the FabPod prototype. This customisation could allow a design to respond to both acoustics and form as design drivers.

I set out some initial design concepts, beginning with a component system and its key elements: a hyperboloid face, timber frame and planar faces to the outside (Fig. 4.04). Materials for these elements were initially left open, though numerous options were apparent for each. I proposed that the frame was once again cut from sheet material, this time using a 5-axis CNC process to allow edges to align with the hyperboloid profile and joints between frame parts to meet as mitres at custom angles.

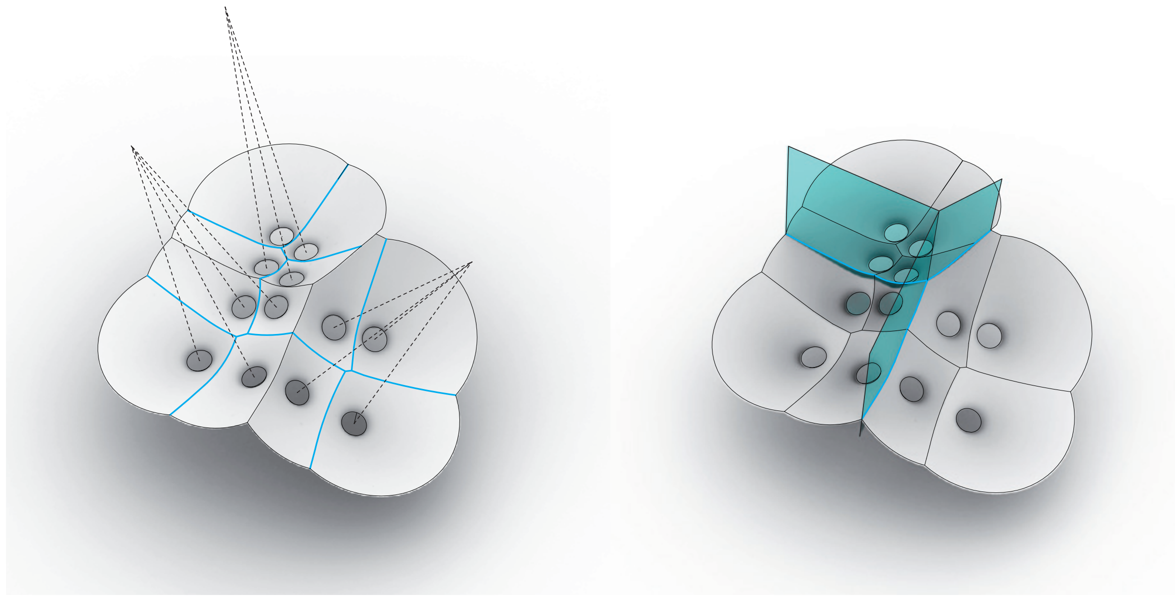

Fig. 4.05. Circular hyperboloids arranged with planar intersection curves - oriented on a sphere (left) and mirrored between spheres (right).

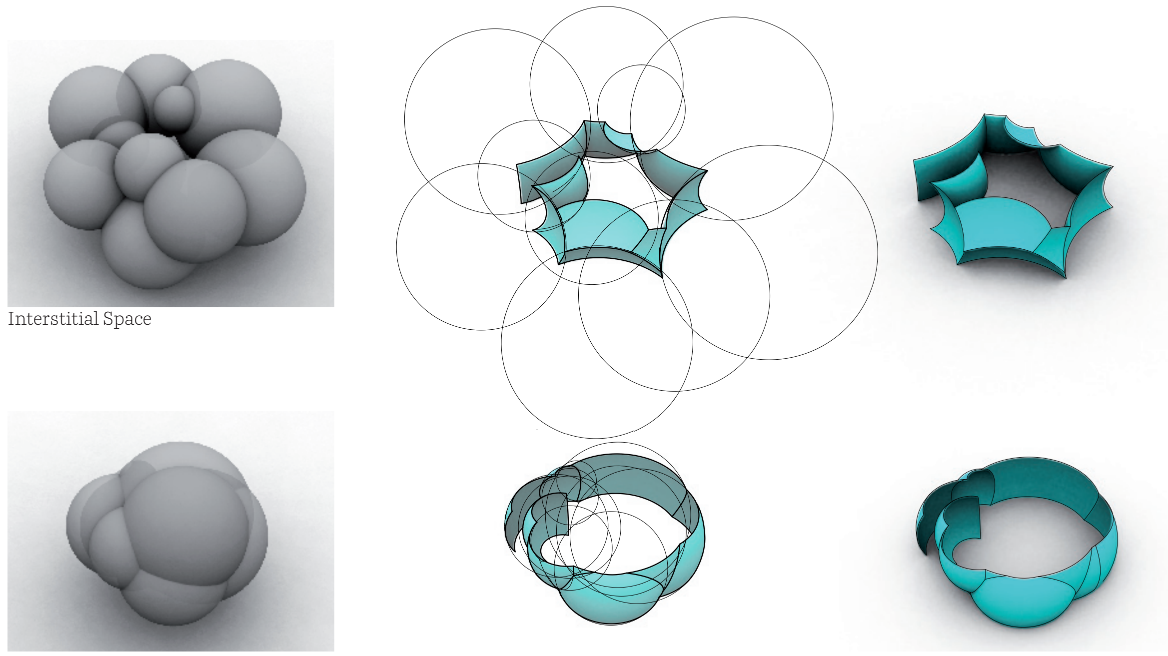

Fig. 4.06. Two families of geometry composed of intersected spheres for the overall form of the FabPod.

Considering this fabrication system, it was important that components have planar edges as they were made from sheet material. These planes are designed for easy stacking and to mark boundaries for trimming the hyperboloid faces. I identified a geometric schema with hyperboloids arranged on spheres (Fig. 4.05) and oriented to a common centre point. In this arrangement the intersection of neighbouring hyperboloids is planar. At a broader scale, spherical forms also intersect in a plane and we can mirror hyperboloids about this. These rules created a space of possibilities, with hyperboloids arranged on forms composed of intersected spheres (Fig. 4.06).

4.2 Modularity in the FabPod Workflow

4.2.1 Creating Plugins as Design Tools

Drawing on the geometric schema discussed above, we set out to explore a broad design space across two scales of intersected spheres and trimmed hyperboloids. Working with Daniel Davis, an original member of the RAS team, we developed a workflow centred on two Activities to set out form (Fig 4.07). Each Activity centres on a parametric model in *Grasshopper* which enabled us to rapidly iterate through design by adjusting of key parameters. This exploration was important not only to better understand architectural expression, but to understand the implications of form and material on the acoustic performance of the structure. To increase iterations and breadth of our exploration, we engaged a class of students and invited external practitioners to generate design options (Fig. 4.08). For these novice users, our parametric models needed to be robust and allow them to simply plug-in and adjust parameters to reliably generate designs.

The first parametric model allowed a designer to set out spherical forms of a room. This required inputs to locate centre points of each sphere and to define a radius for each (Fig 4.09). Further, a designer needed to nominate either a convex or concave form. Daniel and I discussed several options for a robust solution, eventually using a Boolean union to intersect spheres and then selecting a point to nominated as inside the

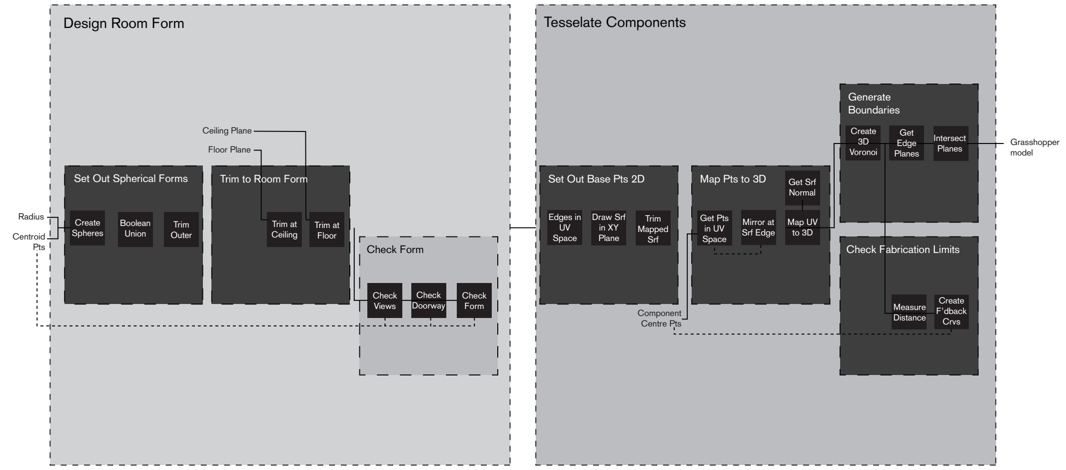

Fig. 4.07. The workflow arrangement of the two design activities of designing form and tessellating cell components across a form.

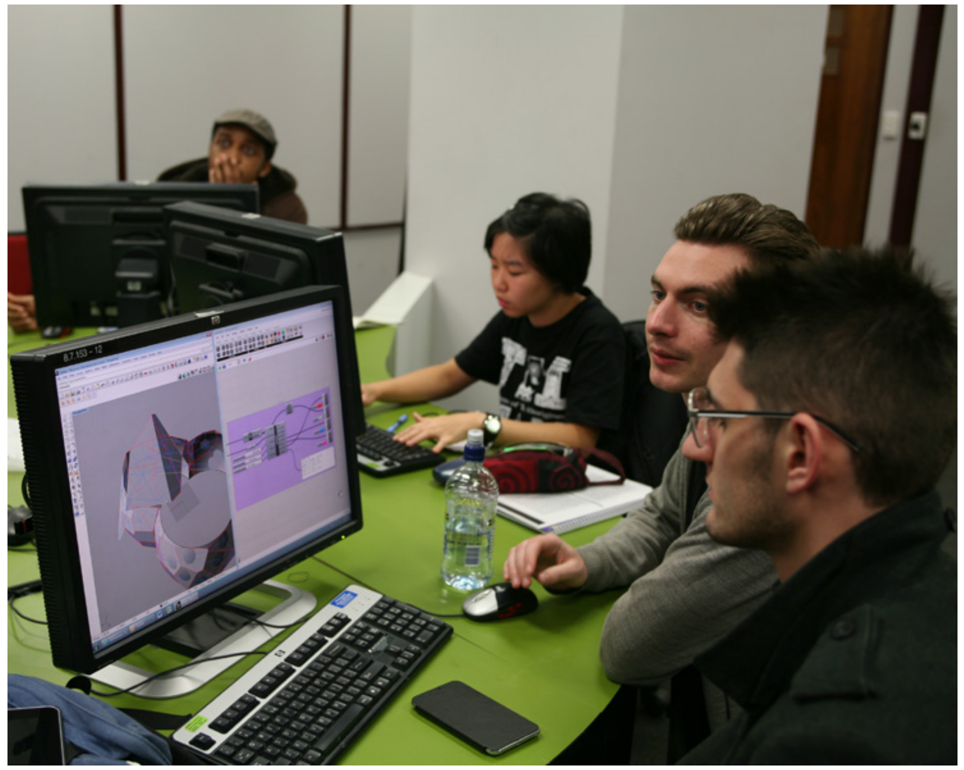

Fig. 4.08. The paramteric design tools being used in a week-long student workshop.

space. The form of intersected spheres was then trimmed at planes representing the limits in relation to the existing floor and ceiling of the space. This arrangement appears straightforward and regularly produces valid solutions. There are cases where it fails, however, for example where spheres are not big enough or too far apart to intersect. We developed the parametric tool to check these cases and provide visual feedback to users in the form of red geometry to highlight problems.

The second design tool enabled the distribution of cells across the spherical surfaces. Again using a *Grasshopper* model, we proposed that circular hyperboloids be located as a point on these forms. We use the normal of the base to define an orientation for the component. To provide an easy interface for design, we approximated the spherical surfaces as flat outline, allowing a designer to place points on a work plane. These points are then mapped back to the 3D form. We then calculate the trimming planes of each cell using a voronoi diagram. This Task is handled by a custom plugin component created by Daniel for voronoi patterns on spherical forms.

With a central axis and trimming edges defined, we could calculate sizes of each component. We measured the distance from the central axis to a corner, and the angles at these corners. Both of these are critical fabrication constraints, relating to the size of base hyperboloid we could manufacture and range angles of mitre joints in frames which we could cut and assemble. In a similar fashion to the first tool, problematic areas were flagged through coloured lines (Fig. 4.10), prompting a designer to edit them.

This workflow spanned two Activities. In each, the parametric models enabled us to undertake a sequence of Tasks. While they were built bottom up through connecting Functions, they had a relatively high degree of modularity at the scale of Activity. This was necessary to control design outcomes to fit with broader elements of the component system and means of fabrication. We created some Tasks for checking geometry, which branched off the sequential workflow at the end of each Activity.

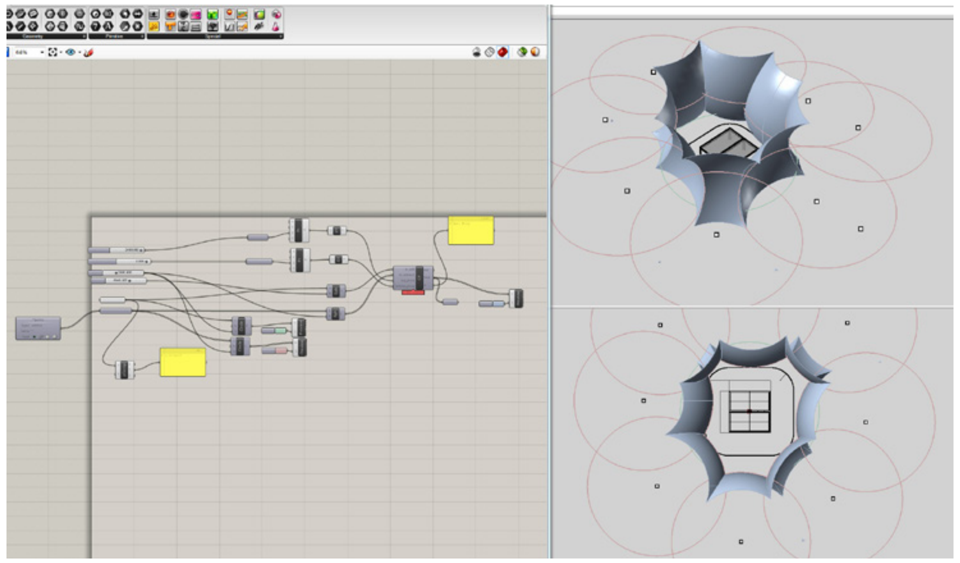

Fig. 4.09. A screenshot of the FabPod design tool for setting out wall forms.

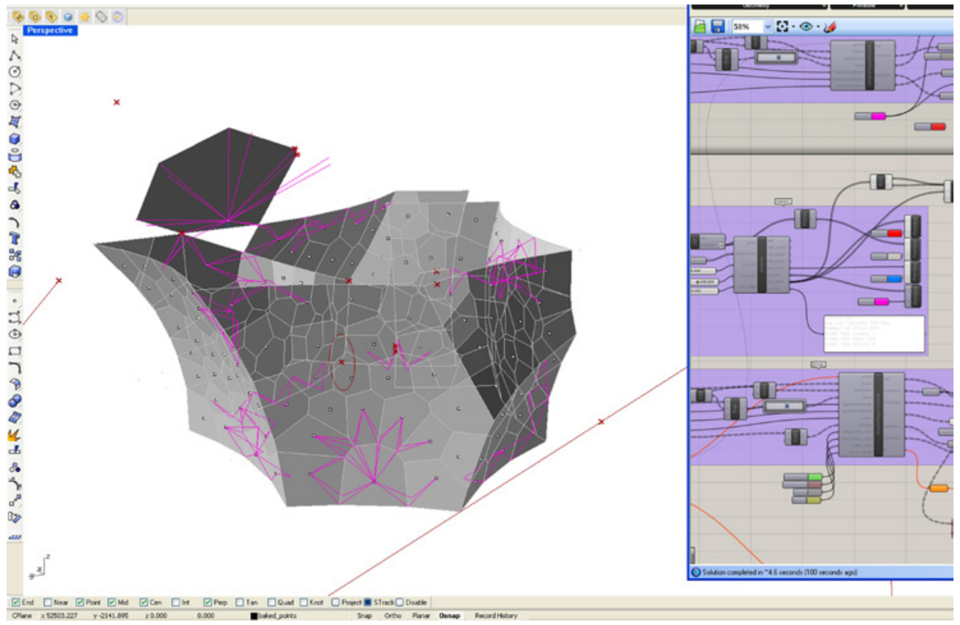

Fig. 4.10. A screenshot of the FabPod design tool for tesselating cell components across a form.

4.2.2 Plugging In Acoustic Design

Another member of the RAS team engaged in the FabPod was Brady Peters who led the acoustic testing and was here engaged to lead research expertise in acoustics. Brady's research expertise includes techniques for modelling sound scattering, which he employed alongside other simulation techniques here. This section addresses the interface of design models with Brady's acoustic workflows.

We used two acoustic simulation packages, firstly the *Pachyderm* plugin for *Rhinoceros* with which we ran a series of conventional simulations on the native model. We also used *Odeon* for more detailed simulations and to verify results from *Pachyderm* (Fig. 4.12). The primary tests undertaken in each package were for Reverberation Time, Sound Pressure Levels and Speech Transmission Index.

As I have described above, our design tools provided geometry at two scales, for the setout and surface articulation of a design. To interface with acoustic simulations, we needed workflows to abstract these designs for specifics of each tool (Fig. 4.11). Both packages use a combination of image source and raytracing algorithms for simulations, requiring a mesh geometry of spaces and forms. To use Pachyderm, the NURBS surfaces of design models were converted into mesh representations using internal procedure in *Rhinoceros*. To use *Odeon*, we needed to manually undertake this translation, approximating the NURBS surface models with triangular mesh faces. Brady deemed that a relatively coarse mesh was appropriate for undertaking simulations, these calculated over approximately ten minutes. Creating more detailed mesh representations, though theoretically achievable, would have required further processing power without necessarily improving accuracy. We created triangular faceted meshes by connecting vertices at each corner with the centre of each component (Fig. 4.13).

A third strand of Brady's acoustic investigation addressed the scattering coefficients of the hyperboloid forms. For this, I provided to Brady digital models showing typical arrangements of cells. These showed the intended scale and density of components. He in turn created two-dimensional section profiles through these models

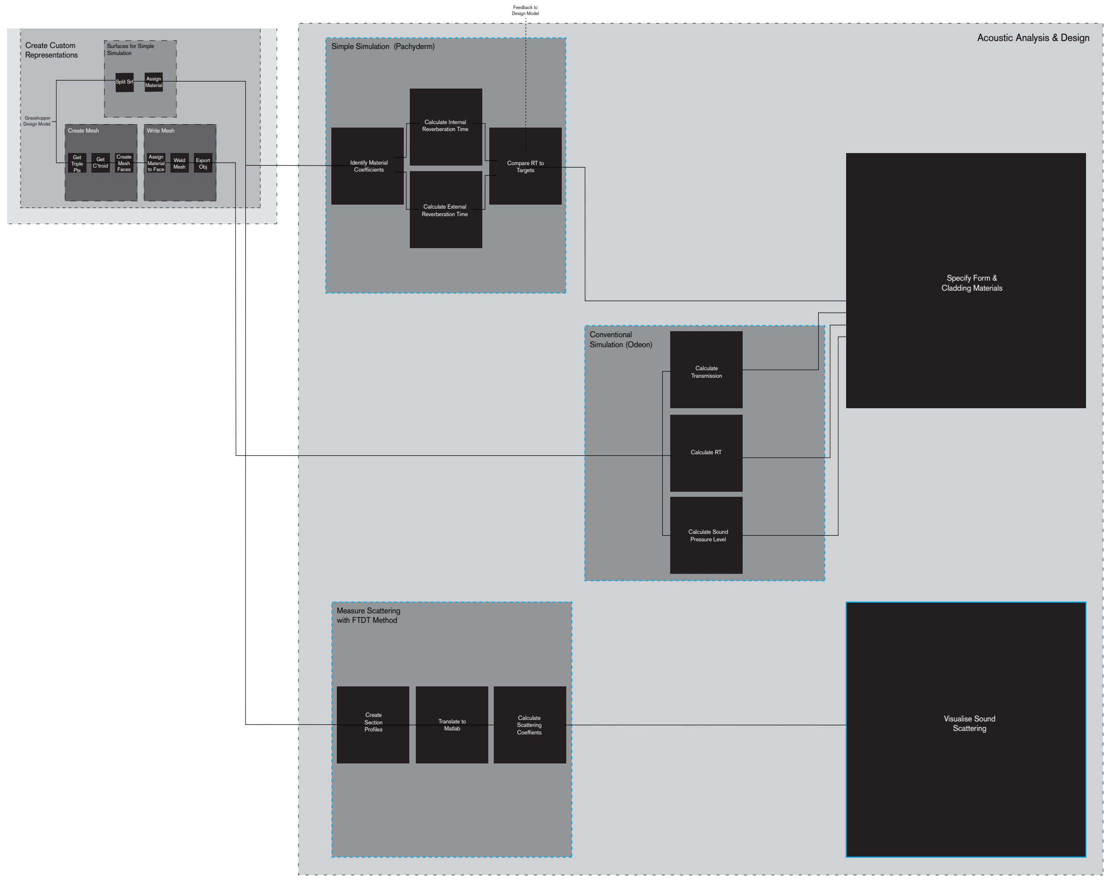

Fig. 4.11. The workflow for analysing acoustic performance with three types of digital simulation.

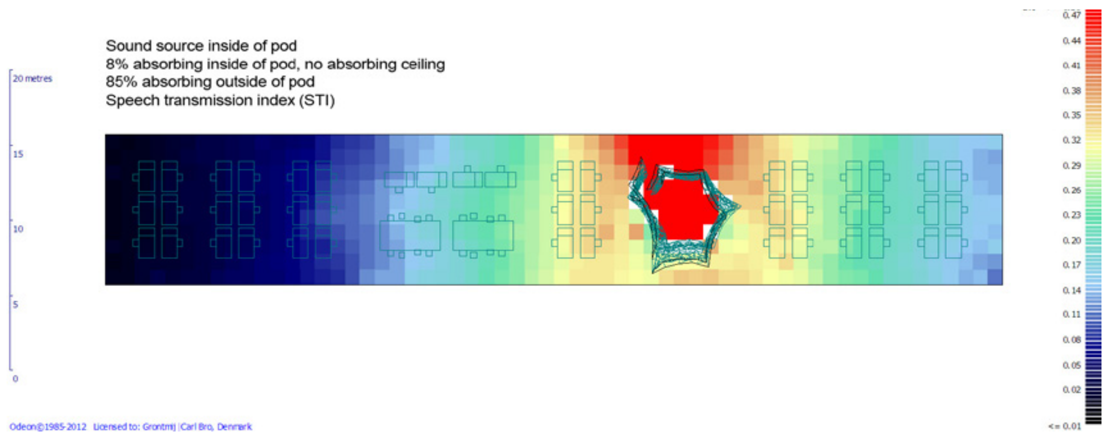

Fig. 4.12. An example of an acoustic simulation in *Odeon*.

to calculate scattering coefficient using the Boundary Element Method in *Matlab*.

This workflow connected across two Divisions of designing form and simulating acoustics. With these connections we could iterate rapidly, proposing design arrangements, simulating acoustics and gaining feedback on the performance of a proposal. Rather than lead to a singular solution, this improved our understanding of a specific design problem and situated acoustics as a primary driver in the design of form and distribution of material around this.

These three lines of simulation were each an Activity within a Division of acoustic simulation (Fig. 4.11). They were undertaken in parallel, and simulation highly modular. Both the simulations with *Pachyderm* and *Odeon* were run through modular software routines. We fed back results to inform our iterative design process, learning about the acoustic implications of our design models. Pulling together results from all three strands, Brady undertook an Activity of providing direction on forms and material distributions. This was again highly modular, drawing on his experience and expertise in acoustics to make decisions and provide design direction.

4.2.3 Plugging Design into Fabrication Models

Alongside acoustics, we also needed to create a clear and consistent interface between our design models and those for fabrication. A pipeline to create fabrication models was developed in collaboration with another of the original RAS team, Alexander Pena de Leon. His preferred platform for detailed parametric modelling is *Dassault Systemes' CATIA*, a platform which excels at handling complex geometry and parametric parts. We created a workflow to connect our design models in *Grasshopper* to become inputs to models in *CATIA* (Fig. 4.14).

Creating minimal models to unambiguously describe intent for fabrication (Scheurer, 2013, 116), we identified a succinct and robust means to represent the design intent. The design is composed of an array of standalone cells, and we captured information for the setout of each of these, composed of:

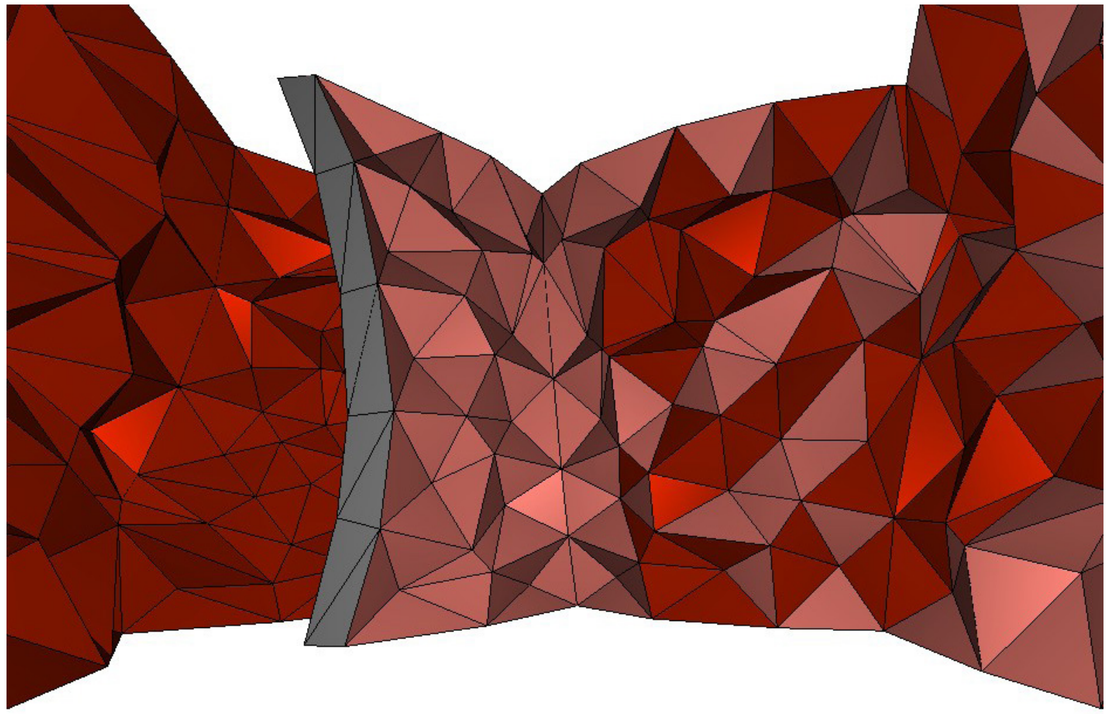

Fig. 4.13. A mesh tesselation of an interior form, showing crude triangular faces suitable for acoustic simulation in *Odeon*.

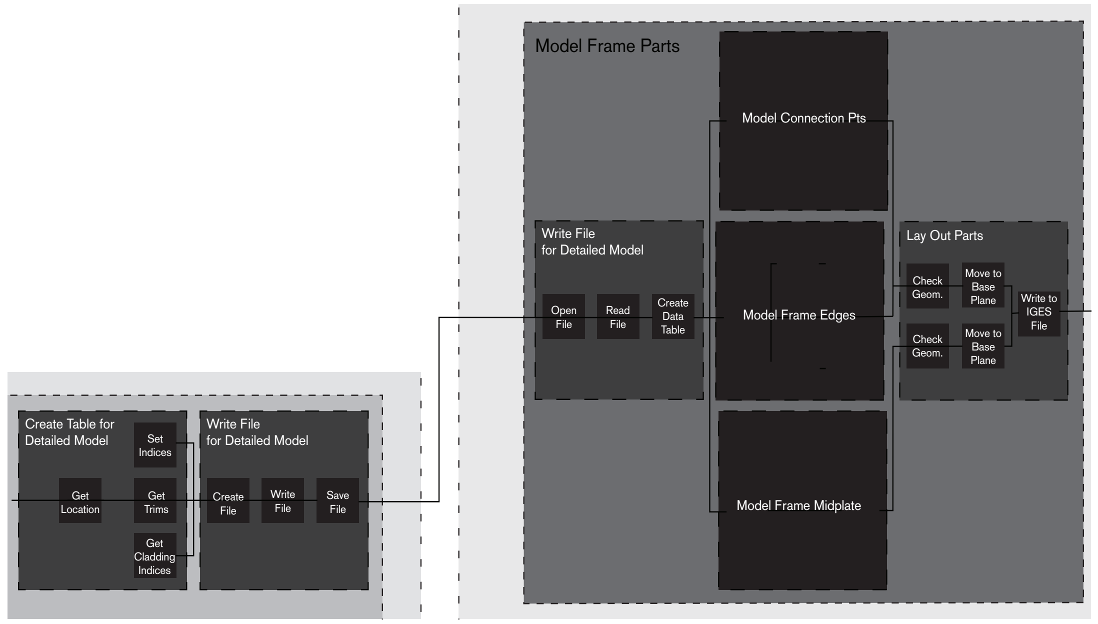

Fig. 4.14. The workflow for translating design information to detailed information for fabrications.

- an index to identify the component
- a point and vector for the orientation of the hyperboloid face;
- the definition of a series of planes at the outer boundaries where the cell was to be trimmed;
- an index to identify the material for the hyperboloid face;
- an index to identify the material for the planar face.
- an index to identify the material for the oculus of the hyperboloid.

To generate the detailed geometry of each cell component, we addressed three aspects of the workflow in parallel. We created custom routines to write and read simple comma-separated files on the either side of the interface between design and fabrication Divisions of the project (Fig. 4.15). In *Grasshopper* the routine was scripted in python. These files could be opened and read through scripts written for *CATIA*. Alongside this, we selected a hyperboloid form to be used across all components. We selected a size and shape which was suitable for acoustic effect and which could be readily fabricated. We defined this hyperboloid form through an equation requiring nine parameters. Finally, we nominated thickness of all materials for the frame and facing materials. In doing so, we partially constrained our material selection on the project but kept open choices of colour and finish.

We input information of cell geometry and material parameters to a parametric model, through which we could generate detailed geometry of all elements. I worked with Alex to clarify details to inform the detailed models. He then created scripts for the Tasks of modelling each type of component. This workflow followed rules to offset and intersect planes and surfaces, and to locate necessary fixings. This enabled us to automate this detailed modelling through a combination of procedural code and parametric relationships, the latter defined manually on a sample part and then instantiated across others (Pena de Leon et al., 2013, 649). With all parts in a single 3D model, we checked for errors and clashes (Fig 4.16). As a final Task, Alex applied further rules to his parametric models in order to arrange all parts flat on a single plane (Fig. 4.17). These Tasks run through scripts and parametric relationships were highly modular, allowing for quick and accurate production of geometry.

4_0,cell_type(hard_soft),cell_cen-
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Fig. 4.15. A sample of the plain text description of a design, interfacing with a detailed fabrication model.

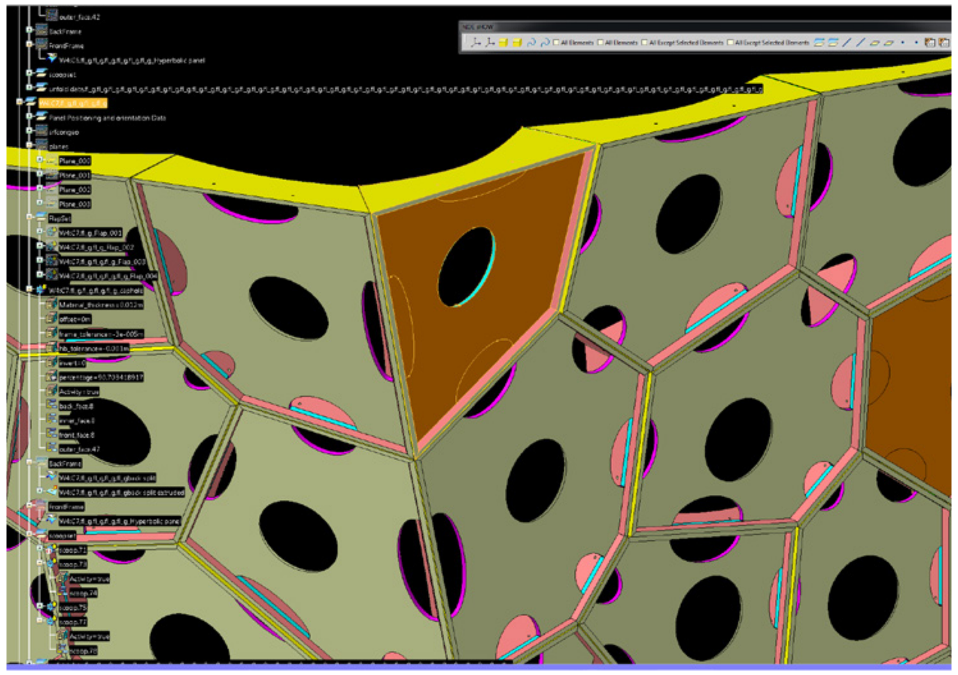

Fig. 4.16. A screenshot of the detailed model in *CATIA*.

4.2.4 Plugging In CAM Technology to Fabricate Frames

With a workflow to generate detailed 3D models of all parts in each frame, we seemed to be close to beginning fabrication. I earlier described that we had designed our components for machining with a 5-axis machine. I identified several suitable machines, initially a 6-axis robot at RMIT and subsequently two *Biesse Rover* 5-axis routers. However, we had trouble selecting a specific fabricator and details of which machine and a suitable CNC file format remained unclear until late in the project programme. Instead, we designed a workflow to prepare fabrication information in an agnostic format which could later be post-processed for various machines.

To translate this digital geometry to fabrication files we needed to identify two types of feature for fabrication, holes for bolt fixings, and ruled surfaces at the edges of parts. Again, we sought ways to describe these in minimal and unambiguous terms, choosing specific geometry to represent each as outlined in table 4.1. Due to limited information associated with the geometry in *CATIA*, we decided that *Rhinoceros* would offer a better environment to create these fabrication files. We exported the parts as NURBS surface models and then modelled geometry of features in *Rhinoceros* using scripts to automate the process (Fig. 4.18).

Type of Feature	Geometry to be Cut	Abstracted Geometry for Fabrication
Drilling	Cylindrical hole	Centreline axis.
Flank cut	Ruled surface	Two rail curves – tip location and angle.

Table 4.1. Geometric definitions used to abstract feature for fabrication for MDF frames.

From these geometric representations of edge surfaces and holes, we then created generic descriptions for machine toolpaths. We identified the Automatically Programmed Tool (APT) language as a suitable, text-based format for this type of fabrication information. Our files describe toolpath locations defined in cartesian coordinates relative to a given work plane. They also describe a sequence for the machine to follow, including rapid movements for efficient operation where the tools are free from material. We also describe actions such as loading a tool and setting parameters of feed and speed rates to describe movement across a sheet and of the

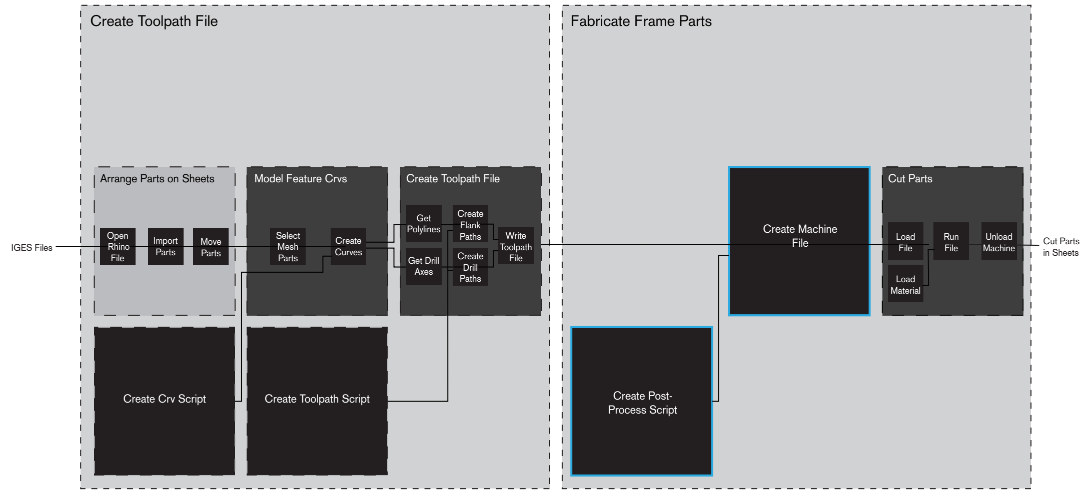

Fig 4.17. The workflow for translating detailed geometry of frames to parts cut from MDF sheets.

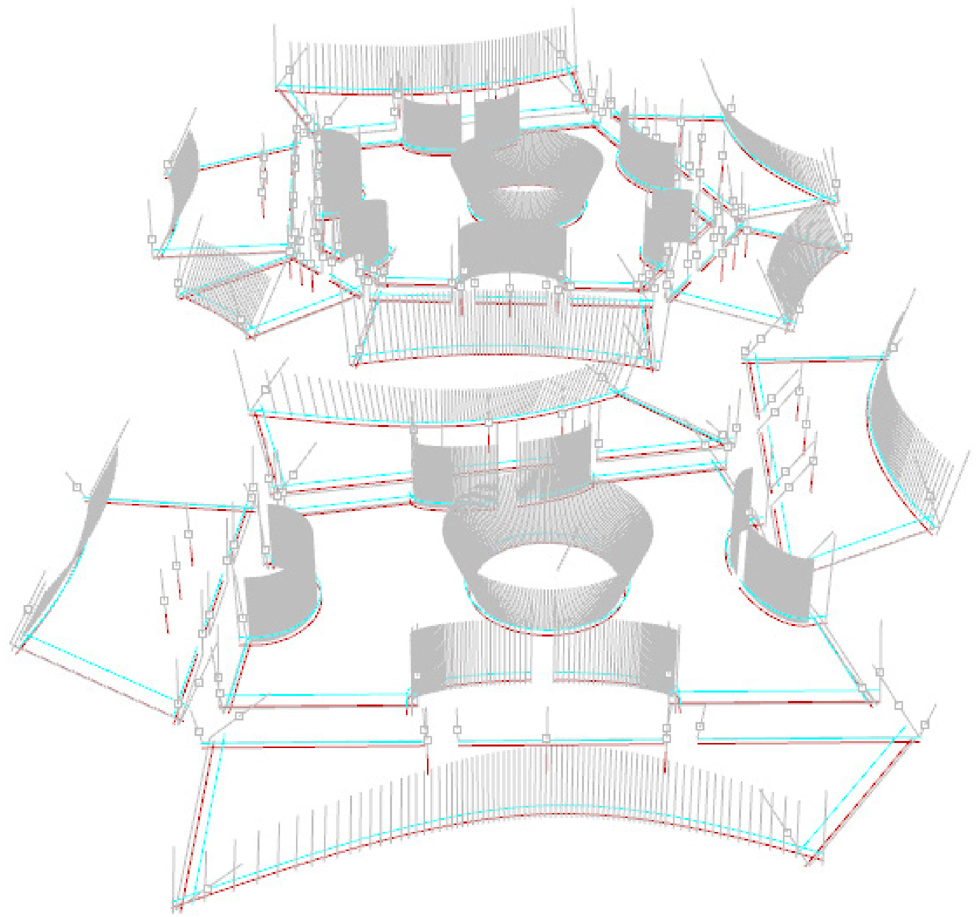

Fig 4.18. A screenshot of abstracted geometry describing fabrication features in *Rhinoceros*.

spindle rotation respectively.

To write these files, we designed an Activity in which a user selects geometry in a desired sequence. In each case we specified drilling operations prior to cutting, in order to avoid the risk of cut parts moving and drilled holes therefore being incorrectly located. The manual input we used was chosen as a pragmatic response to a two-day window to produce a functioning workflow. It allowed us to check quality, and for 80 sheets, we only needed a few hours to create files.

To create these files we followed approaches which are available through a number of off-the-shelf software packages. We followed a series of Functions to divide curves and create toolpaths from the geometry in 3D models. Toolpaths were represented as a sequence of locations and orientations. These were identified by dividing curved elements into discrete lengths which deviated from a curve less than a nominated tolerance of 0.1mm.

With a collection of APT formatted files, we could postpone the final step of producing files with specific machine information until those machines were identified. The last step of writing these files required that we transform the locations and orientation vectors of the toolpaths to specific coordinate systems for each machine. We outsourced this Task to one of the machine operators, who themselves had custom scripts to automatically create machine programmes in Numeric Control (.nc) format. For fabrication we ran these programmes in parallel on two Biesse Rover machines (Fig 4.19), requiring just under 15 hours of cutting time.

As with the workflow to create the detailed model, this ran through a series of scripted routines. The Activity of creating toolpath files involved a series of Functions which we manually worked through. By creating a series of scripts, we made Tasks highly modular, with basic manual selection of inputs (Fig. 4.17). The second Activity of fabricating Tasks involved similarly modular Tasks to create file for machining. The Tasks of cutting parts was manual and linear, and ran without errors. We subsequently assembled frames, working through further Activities with John Cherrey to ensure frames were within tolerances of 0.2mm across any assembly (Fig. 4.20).

Fig. 4.19. Cutting frame parts from mdf sheet using a Biesse Rover 5-axis router.

Fig. 4.20. Frame parts assembled to test assembly workflow and tolerance.

4.2.5 Plugging In Industry to Fabricate Hyperboloids

I described earlier that the hyperboloid components were based on a common shape and trimmed to the unique outline of a cell. The volume of parts, 180 in total, was suitably large for us to engages external fabricators to create these repetitive elements. We created these from three materials to drive a variety of interior finish which could be arranged to help tune acoustic performance.

Working once again with John Cherrey, we set about identifying suitable materials and fabrication processes for these curved forms. We selected two – spinning metal using a lathe, and vacuum forming heated plastics. Both processes can form doubly-curved parts by stretching a sheet material over a form. We found local suppliers with capacity to produce our order and negotiated with them to check geometric limits related to material stretching and finish.

In our digital models, we represented hyperboloid geometries using an equation with nine parameters. We could not communicate this mathematical representation to external fabricators in industry. Instead we created surface models of these hyperboloid components, representing the interior faces of each, representing these surfaces in unique terms to each fabricator (Fig. 4.21).

The metal-spinning company specified that they make the tool which was to be mounted on a lathe. We supplied a digital CAD drawing to them describing the desired cross-section hyperbola curve. We then sent them a laser-cut template for checking accuracy of the shape. The company fabricated a tool from laminated sheets of MDF, manually machining a rough blank in to the specified shape. Once this was checked for accuracy, flat discs of aluminium were readily formed across this into the desired shape (Fig 4.22). Once fabricated, these hyperboloids subsequently anodised for a high quality of finish.

The plastic forming company were happy to use a female tool which we made at RMIT and supplied to them. We created this from laminated layers of plywood, using a CNC router to machine a blank to a deviation of less than 0.2mm from the desired

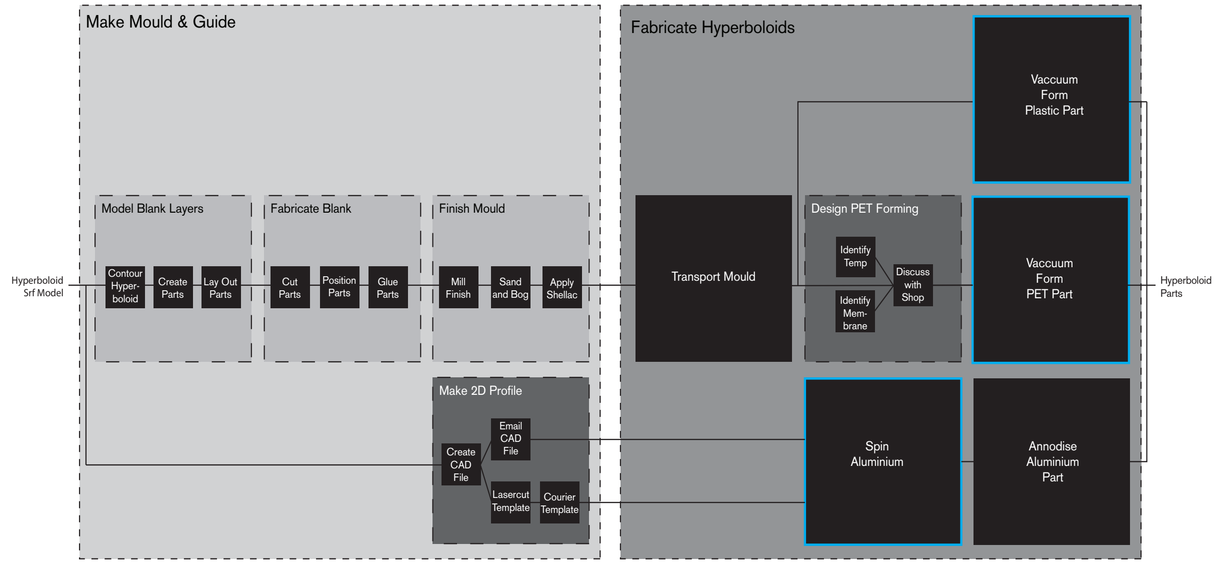

Fig. 4.21. The workflow for fabricating hyperboloid components from three materials.

Fig. 4.22. Comparing our lasercut guide with the tool created for spinning aluminium hyperboloids. (image: John Cherrey).

shape (Fig 4.23). We finished this with a small amount of hand sanding and applied a coat of shellac to the surface.

Two types of plastic were formed on this mould. Firstly, a matt white acrylic was selected to provide an acoustically reflective surface (Fig. 4.24). Alongside this, we selected an acoustic felt product called *WovenImage Echopanel*. This is manufactured from PET and is absorptive (Fig. 4.27). As such it is permeable and our supplier used a silicone rubber membrane for forming this under vacuum. We worked alongside the company to resolve details such as the best temperature for softening the PET.

This workflow has contrasting degrees of modularity in each of the two Activities undertaken. Our selected suppliers provided hyperboloid parts through a series of highly modular Tasks. They worked to agreed tolerances as is conventional for industry suppliers. In contrast, the in-house fabrication of the mould demanded that we work through a sequence of Functions. This reflects that our workshop did not have specific tools and systems in place for producing mould nor did we have any routines for creating 3D models of these.

Fig. 4.23. Milling a finish to a plywood hyperboloid mould, subsequently used for forming plastic hyperboloids.

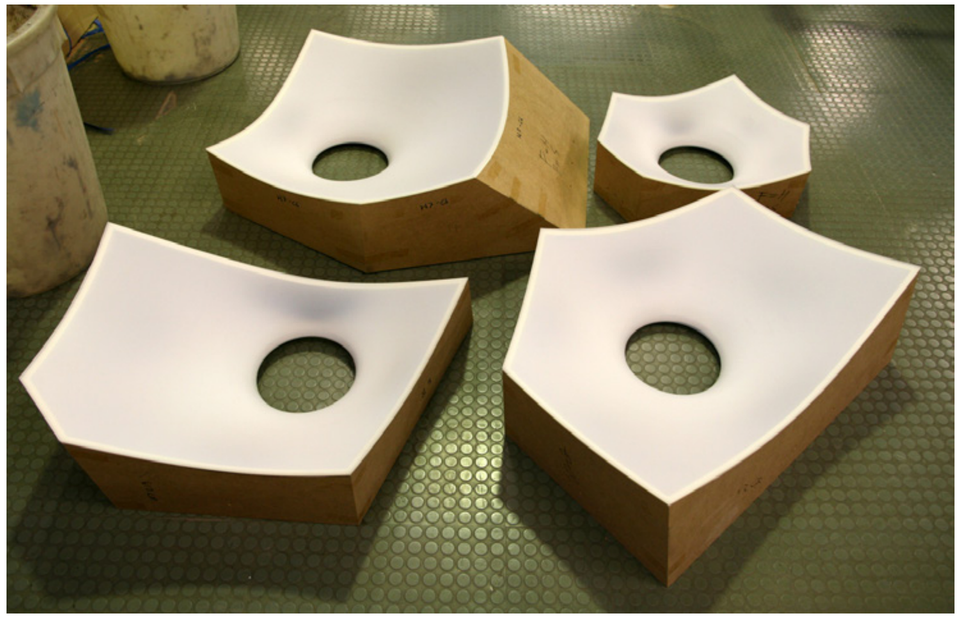

Fig 4.24. Four component cells with white acrylic hyperboloid faces. Each cell has the same hyperboloid form with a unique trimming shape.

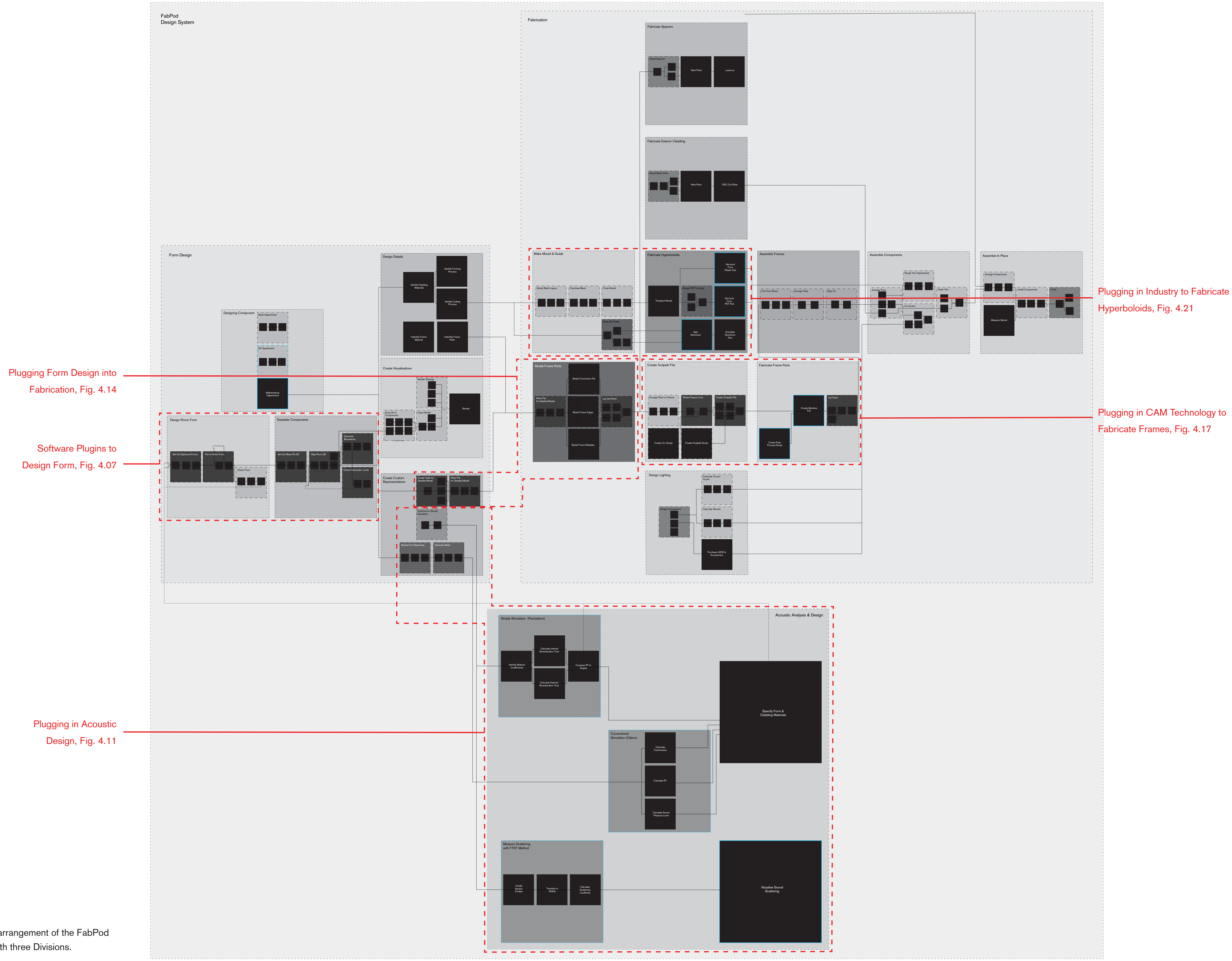

Fig 4.25. Overall arrangement of the FabPod Design System with three Divisions.

4.3 The FabPod Design System

Over a three-month period, we developed the range of Activities and Tasks discussed above. Like all projects, this discrete period introduced constraints to the project. Contrary to a conventional approach in which a form is conceived and to which detail is incrementally added, here we developed and refined workflow and detail without making a design model. Our efforts centred on the design of process and integration of these into a Design System to deliver a FabPod prototype (Fig. 4.25).

At a broad scale, the Design System is composed of three loosely bounded Divisions, addressing the design of form, fabrication and acoustic simulation. These Divisions capture multiple further levels of detail related to distinct project roles. I have introduced a series of collaborators and each took leadership within a single Division to implement workflow drawing on their specific expertise. The leadership of these individuals helped to define boundaries, albeit fuzzy, between Divisions. I have discussed two workflows above which span Divisions, connecting architectural design models with acoustic simulation and fabrication. In these cases, I have aligned Divisions to the engagement of individual collaborators, though this could be debated. For example, specific Tasks such as creating custom mesh representations of design models could be argued to be part of the acoustic Division, though they were not created by Brady.

The Design System holds many moments where fabrication drives design. I have described earlier that we began design with a concept for a component system. This responded to both opportunities and limitations of earlier research as well as available tools and techniques for fabrication. For example, I proposed early that the frame of each component be cut with a 5-axis machine. This helped to enable us to design tesselation patterns in which component shapes were varied within limits. This flexibility further helped drive relationship between component and whole, enabling us to explore spherical geometries at the scale of the enclosure.

We were similarly able to use acoustics simulation to drive design, though this differed from the quantified and hard limits of fabrication. Through iterative design and

Fig. 4.26. Information flow between form and acoustics, with divisions aligned to the roles of key individuals.

Fig. 4.27. Cells with hyperboloid faces fabricated from WovenImage Echopanel, arranged in the workshop during fabrication of the FabPod prototype.

testing in a one-week workshop, we refined our understanding of the acoustic performance of spherical wall surfaces, hyperboloid tessellations and various distributions of material. In total, with a team of students we produced over 500 design versions. We realised relatively early that the concave surfaces internally would better serve a diffuse interior. As such we focused on various configurations and scales of these. The proportions of various material finishes and the distribution of these around a design form required much more detailed analysis and a nuanced design response. As such, we did not converge to a solution but rather found sweet spots between form, material and acoustic performance to create more sophisticated designs.

At times alongside this, fabrication also served design. We sought techniques which were suitable to forming hyperboloids, finding suppliers for both metal spinning and plastic forming. We similarly built chains of digital information to model detail and generate machine files for parts. These created workflows to meet specific demands of the design. This bottom up approach to fabrication can result in a low degree of modularity at the scale of Task and Activity. To control the quality of parts, we implemented strict sequences, thereby increasing the degree of modularity through these core workflows for delivery.

4.4 The FabPod Prototype

The full-scale prototype was designed and constructed over a 6-month period. It is composed of 180 cells, with frames held over 1000 unique sub-components, themselves cut from 84 sheets of MDF. We assembled cells in a workshop and transported them to site (Fig. 4.28) for installation by a small team. This team fixed components together within desired tolerances using off the shelf bolts and t-nuts. We assembled all 180 cells in just over two days, with further time needed to install electronics and fix final panels to the exterior (Fig. 4.29).

The FabPod sits as a sculptural presence within the open-plan office space of the Design Hub, two-thirds of its exterior is covered in *Echopanel* to absorb sound in this large environment. The remaining 60 components are clad in a translucent acrylic,

Fig. 4.28. All 180 cells on site in the Design Hub, ready for assembly of the FabPod prototype.

Fig. 4.29. Assembly of the FabPod on site in the Design Hub was completed by a small team.

to highlight lights which are distributed around the walls. The internal space is big enough to hold existing furniture and seat eight people (Fig. 4.31). This has inverse proportions of hard and soft surfaces to the exterior. One third of components are clad in Echopoanel, with a cluster around the entry, designed to reduce sound transmission through this open doorway. The other two-thirds of components are clad with reflective surfaces of spun aluminium and formed acrylic.

Through the FabPod I explicitly sought to prototype a design approach which could support customisation at the scales of both component and overall form. The geometric and material customisation is evident here and shaped through the exploration of relationships between form and material with acoustics, and further with fabrication and the FabPod has provided a persistent model for testing inquiry. Research has addressed architecture and technology audiences, as well as acoustics (Alambeigi et. al., 2016) and ethnographic studies of behaviour and attitudes (Pink et. al., 2017). This has extended understandings of the FabPod, it's role in the Design Hub space and within the larger identity of the institution which owns it. I have been involved in the design of a subsequent FabPod, as discussed in Chapter 7.3.

To deliver the enclosure, we also prototyped many aspects of production. We refined workflows to a degree which enabled a linear flow from the design of a form. I have highlighted three aspects of this, in the parametric models to design forms, and subsequently to generate detailed design models, through to the workflow to create files for CNC fabrication. As I have described, such modular but resolved process underpins systems for mass-customisation. Here, however, our experience highlights the gaps to larger scale production. We experienced a series of delays in delivering the prototype. These range from problems within the team such as incompatible software files, to problems beyond our control including the accidental destruction of MDF frame parts in transport. This highlights that despite producing specific knowledge, major gaps remain to this research having impact beyond the one-off project.Further detail on the acoustic simulation and design tools used for the FabPod prototype has been published (Peters et. al, 2013). Further detail on the connections between design and fabrication can also be accessed through publications (Williams, N. et.al., 2015).

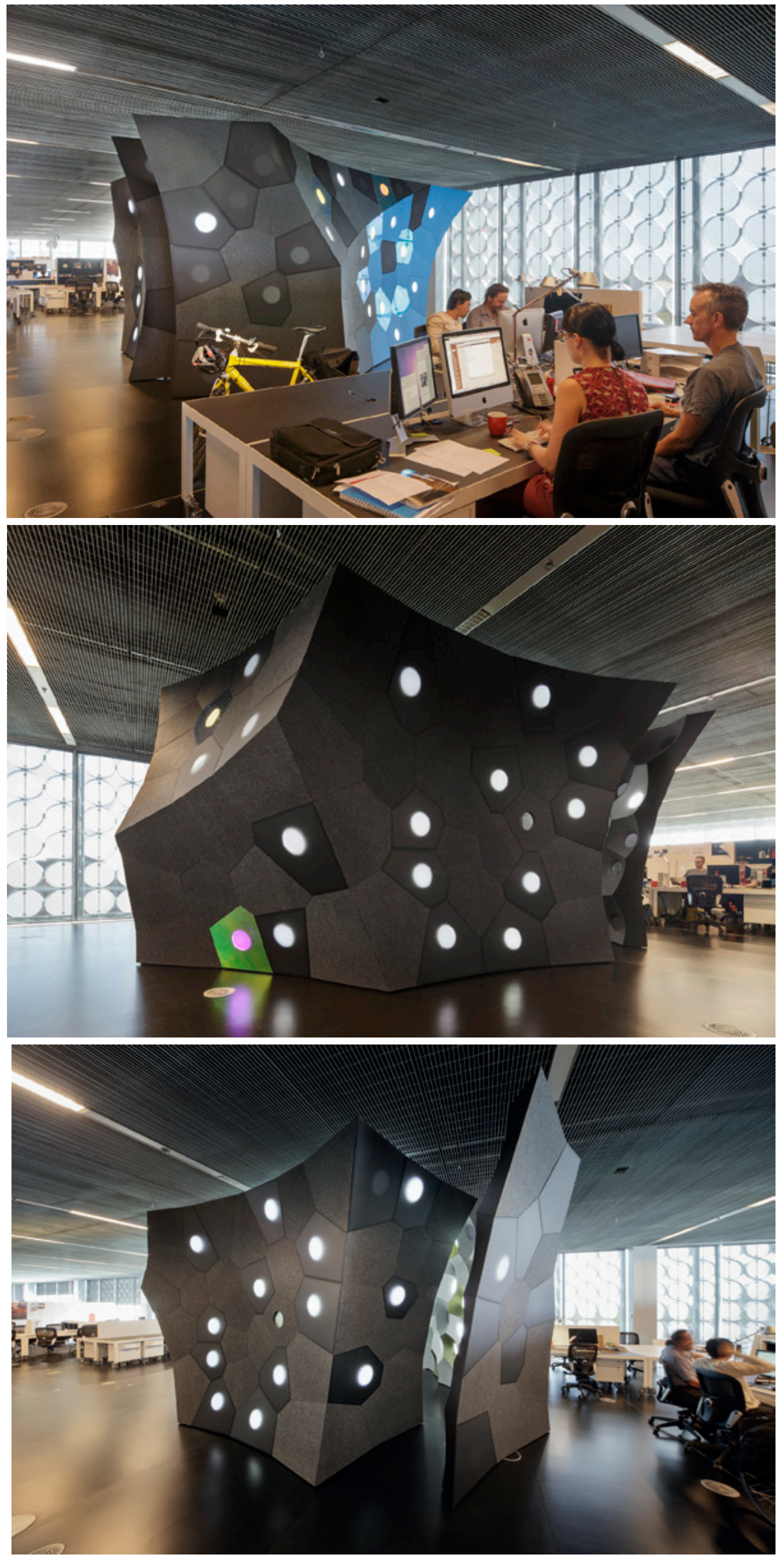

Fig.4.30. Images of the FabPod, installed in the Design Hub at RMIT. (images: John Gollings).

Fig.4.31. Interior of the FabPod prototype. Image: John Gollings.

SOUND BITES

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John Cherrey, Architecture and Design, RMIT University

Sascha Bohnenberger, Bollinger Grohmann Engineers

Exhibition Curators:

Lawrence Harvey

Jon Buckingham

Suzanne Davies

Exhibition Support:

Jeff Hannam

The Sound Bites City exhibition and this installation were hosted and supported by RMIT University Gallery,

Student Assistants:

Jingyi Yang

Lijun Loy

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Yee Shuian Sang

Pouria Zoughi

Hannah Hussin

Yunlu Huang

Ren Zacq Wong

Menghao Yuan

Hiufei Choi

5.1 The Sound Bites Shell Background

5.1.1 Research Premise: Bending-Active Material Performance

Sheel structures have received much research attention for their perceived efficiencies in structural performance, being self-supporting and capable of carrying external loads and transferring within the surface of shell (Adriaenssens et. al., 2014, 1). Gridshells are a subset of shell structures. They are created from elastic, anisotropic materials such as wood, with all members finding an equilibrium state, a so-called bending-active condition (Lienhard et.al., 2013, 138).

Many fundamental terms and concepts around gridshells are attributed to Frei Otto. Otto's built research is exemplified by projects such the Multihalle of the Garden Exposition in Mannheim (1975, Fig. 5.01), which still stands today and spans over 35m to create a large hall. It is a post-formed gridshell, a type with potential for rapid installation on site through the simple bending on-site of a network of straight members into a desired form (Fig. 5.02). Timber is regularly used for both its relatively low torsional stiffness, making it suitable for bending into such doubly-curved shapes, and for relative ease in fabricating joints (Harris, et. al., 2004). Over the decades since the Mannheim project was completed, a number of notable timber gridshells include the Japan Pavilion for the Universal Exposition in Hanover (Germany, 2000), the Weald and Downland Museum in West Sussex (United Kingdom, 2002), and the Savill Garden Building in Windsor (United Kingdom, 2006).

I have already made reference to Frei Otto's research and built structures as exemplars of analogue computation, with connections to antecedents such as Antoni Gaudi. Interest in gridshells has blossomed recently through digital platforms which allow the simulation of loads. In his design process, Otto used scaled, material models to simulate and generate form (Fig. 5.02), and the term form-finding has become synonymous with such a design process. Nowadays, digital form-finding has become accessible to a broad community of designers exemplified by examples such as Kilian

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Fig 5.01. The Multihalle Mannheim, a post-formed timber gridshell by structural engineer Frei Otto.

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Fig 5.02. Aerial view of the curved form (left) and the form-finding model used for design (right) of the of the Multihalle Mannheim.

and Ochsendorf (2005) and the physics simulation plugin for *Grasshopper* named *Kangaroo* (Piker, 2013).

Using digital form-finding tools, researchers have recently sought to explore the formal possibilities and rapid assembly of these systems. Leading examples include the gridshell tectonic investigations by Cabrinha (2008) and Cabrinha and Kudless (2012, Fig. 5.03). This latter work was designed and built in a four-day workshop at SmartGeometry in 2012, highlighting the potential to rapidly iterate through design and prototype such a complex form.

5.1.2 Functional Brief: A Device for Art Soundscapes

The *Sound Bites City* exhibition was the inaugural presentation of a major collective of sound art works owned by RMIT University, opening in September 2013 (Davies, 2013). The sound art collection includes works by several major international artists created for a spatial sound experience and played through multiple channels arranged in space. Many museums are beginning to feature such shows, though they typically have minimal architectural features (Fig. 5.04). In contrast, for the *Sound Bites City* show I was commissioned to design a temporary installation to provide a spatial device to complement the aural performance of works.

A simple brief called for spaces for audiences to experience the art works in several modes. The primary technology was a 24-channel audio system and a primary performance space was required in which groups could gather while a piece was played, listening in relatively passive modes. A more active space was also requested to enable individual audience members to move around the space while a piece played.

The exhibition was hosted by RMIT Gallery. This has two exhibition spaces, and I proposed a major installation for the larger of these, covering approximately 14m x 11m of floor space. The installation needed to be free-standing, with existing walls and floors left undamaged. Suspended lighting tracks located at just higher than four metres above floor level constrained the height of the installation. Furthermore, a series of

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Fig 5.03. A timber gridshell designed and prototyped through the four-day workshop led by Mark Cabrinha and Andrew Kudless at SmartGeometry, 2011.

Fig 5.04. The space and sound equipment arranged for a performance of *The Portal.*

access ways needed to be maintained for safety through the duration of the exhibition. These constraints suggested a lightweight installation which could be rapidly installed.

5.1.3 Prototype Focus: A System for Shared Design

I identified that a gridshell would be both a pragmatic solution and one with significant research potential. The driver for this research prototype lies in the cross-disciplinary collaboration required for design and delivery. Beyond a simple trade-off of form, performance and fabrication, this demanded an intimate rellationship between the three. The curators were intrigued by parallels of this to the composition process of sound art (Davies, 2013, 3) and I was able to propose a compelling arrangement of a significant size which promised to complement the aural ambitions of the exhibition.

Through discussion with the exhibition technical staff, we identified a preferred speaker layout using radial grids to set out speakers equidistant from the centre of the performance space (Fig. 5.05). By arranging speakers at consistent distances, the staff aimed to provide a good listening experience while enabling relatively easy tuning. Speakers were arranged at three heights, with large speakers and subwoofers concealed under a raised central platform and other layers to be suspended within the space. We further clarified key audience modes: a passive, seated area near the centre of the speaker arrangement; a series of individual listening stations where audience stood; and an active mode in which audience moved through the soundscape. These modes were arranged as a central performance space surrounded by a promenade along which listening and reading material could be arranged (Fg 5.06).

This arrangement of speakers and audience modes was matched with an architectural response described as a torus. I proposed that this sit in the gallery space with the audience moving through and around it. To tackle the project, I assembled a design team spanning three key areas of expertise: architecture, structural design and material craft. We surveyed post-formed gridshells and found few examples which pursued asymmetric forms. With this ambition in mind, we made further design decisions such as using a double-layered system of laths between two curved edge

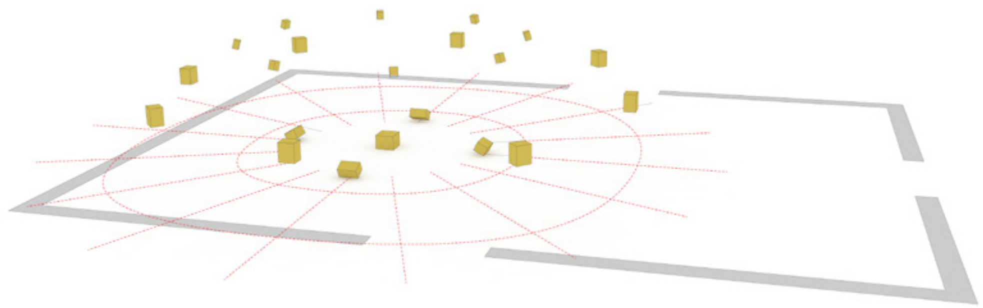

Fig 5.05. The proposed arrangement of 24 audio speakers in a radial pattern and at three heights.

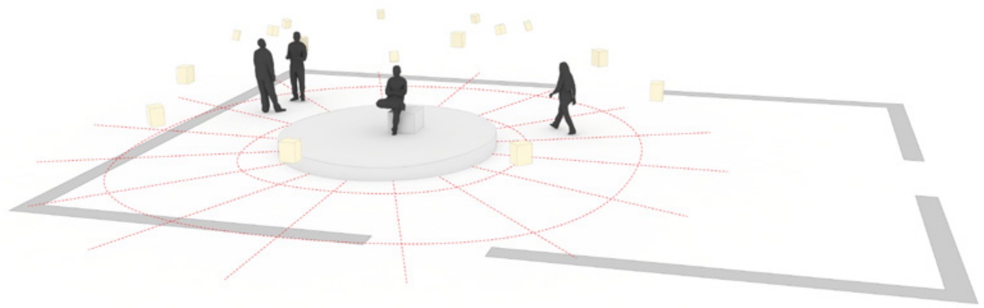

Fig 5.06. The proposed torus design, with timber laths spanning between inner and outer edge beams.

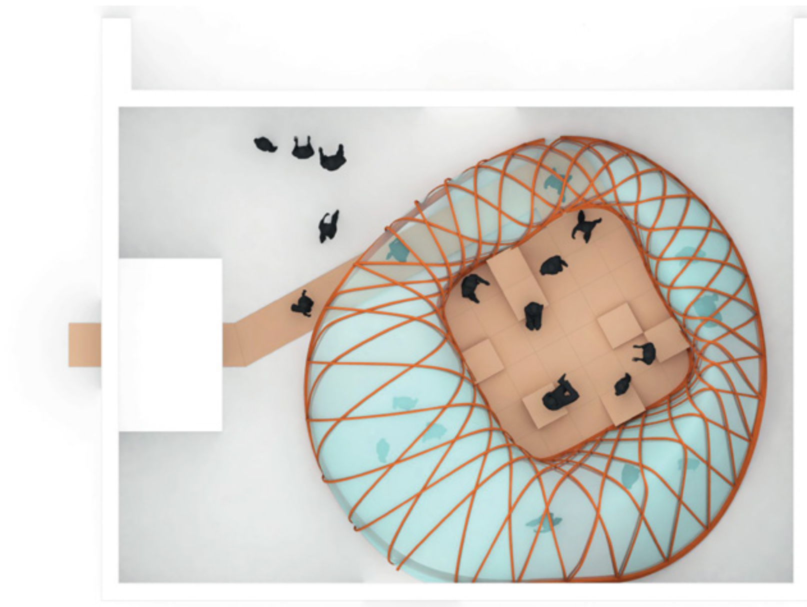

Fig 5.07. A concept drawing for the torus design showing a plan view of the gallery.

beams (Fig. 5.07). With a supporting team of students, we had a six-week period to design and prototype the structure in time for the opening of the exhibition.

5.2 Modularity in the Sound Bites Workflow

5.2.1 Plugging a Sketch into Formfinding

To win the commission from the curators and gallery team, I produced a series of visualisations for a schematic design, describing key spaces and sound equipment. The digital model used for these visualisations had little connection downstream to detailed design of the gridshell. To begin detailed design, I stripped out much detail from existing models to reach minimal definition of a simple set of curves . This formed a diagram which we could use to drive form-finding processes and generate more detailed geometry. The transition from schematic models to this detailed setout involves us shifting scales in Workflow, from Tasks to finer grain Functions for a generative design approach (Fig. 5.08).

To create a detailed design model of a gridshell, we started from two curves defining inner and outer edges of the Torus form. I could manipulate these curves in plan dimensions to control form and then generate a further series of four curves interpolated between these extremes. This was a two step process of interpolation in a single ground plane and then manually editing the height of these by manipulating control points. In manipulating these and the perimeter curves, I was designing both form and access points around the structure.

From these six setout curves, I developed a workflow in Grasshopper to drive the process through a flexible model. I first lofted the setout curves to create a rough setout surface for the shell (Fig. 5.09). Using the base surface and edge curves, I could then create a rough setout for laths. For this, I divided the two edge curves evenly along their length to locate an even set of end points for lath axes. I generated geodesic curves between a point along each of the outside and inside edge curves, describing the shortest paths across the base surface. Through offsetting the lists of end points to

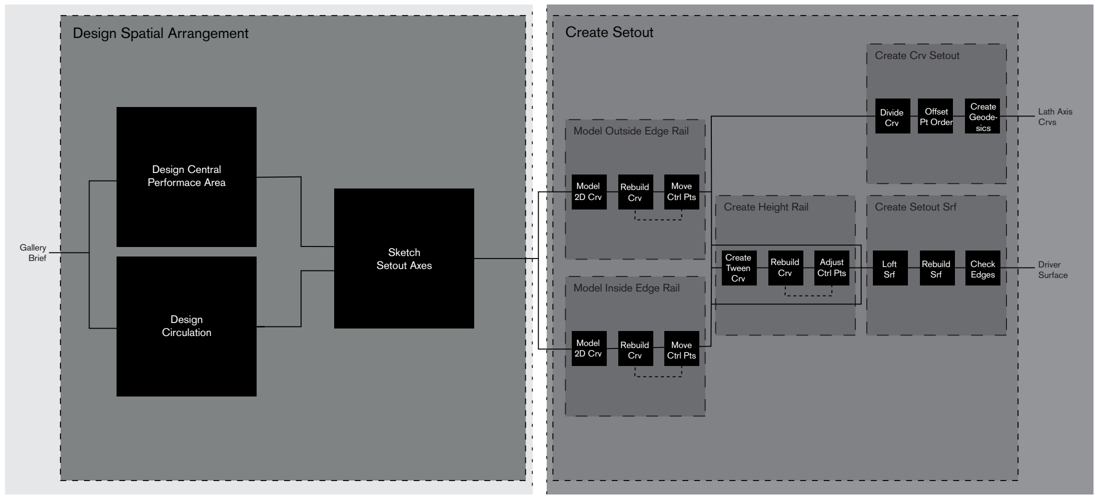

Fig 5.08. The workflow arrangment for setting out data for detailed design of the gridshell.

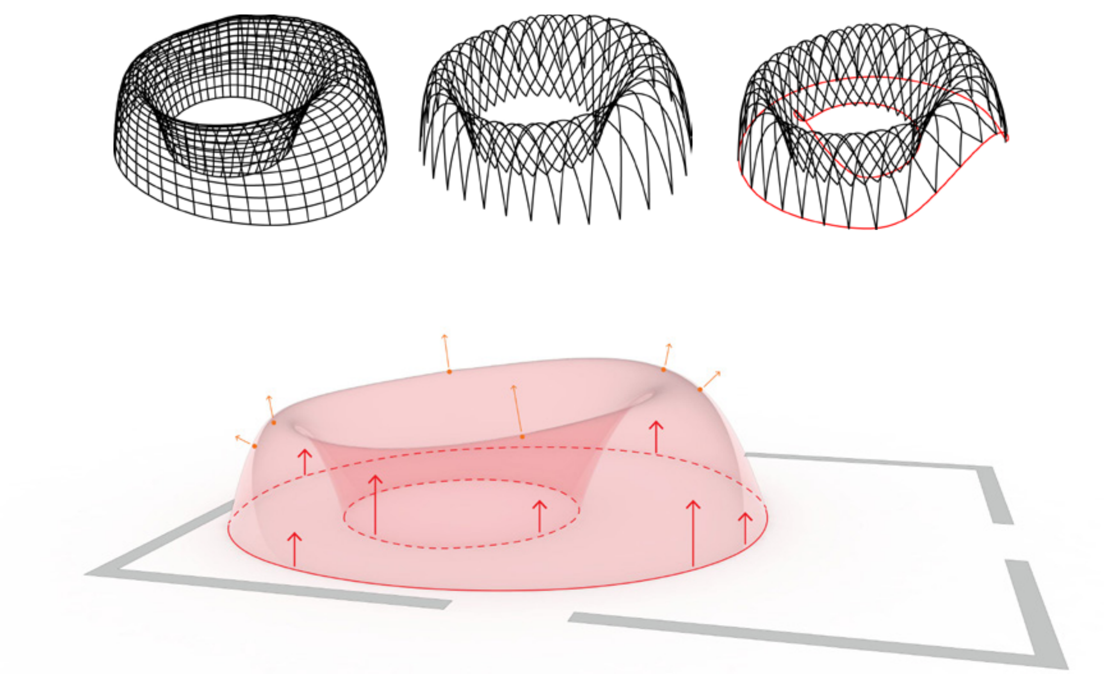

Fig 5.09. Steps in the setout of surface and geodesic curve (top) and the edge curves and control surface generated as a starting condition for detailed design of the gridshell (bottom).

avoid those opposite each other, I defined axes running diagonally across the surface and intersecting with others to form a network of three- and four-sided subdivisions within the surface.

5.2.2 Plugging in Tools to Relax a Surface

With the setout geometry as a base for the detailed design of the gridshell, we could embark on form-finding exercises to generate a suitable form. This process connected architecture directly to considerations of structure and material. I collaborated on this form-finding with a small engineering team, led by Sascha Bohnenberger at Bollinger Grohmann Engineers. Sascha has strong skills working with parametric models and Bollinger Grohmann have developed a suite of structural design tools which we used through the *Karamba3D* plugin for Grasshopper.

We considered several broad approaches to designing funicular gridshells in which loads act as compression within a structure (Adriaenssens et. al., 2014). Some approaches use dynamic relaxation to deform a network of member under load (Kilian and Ochsendorf, 2005). This results in irregular spacing between nodes within the network. Alternatively, techniques have been developed to adapt the form of a mesh to a target while constraining distances between connecting nodes. We used a mixed method in this case, with distances between connections varied to an extent but constrained within limits.

The workflow to engage dynamic relaxation spanned two Tasks (Fig. 5.10), once again created in *Grasshopper*. The first of these was composed of a series of Functions to complete tasks to create specific inputs for simulation. From the setout surface and lath axis curves, we calculated a network of points of intersection between laths. This served as a starting condition for our simulations, to which we applied simple loads. These loads included an assessment of self-weight, evenly distributed across this network of points, and local loads of speakers which we applied to specific points within the network. We fixed in place the location of points along edges (Fig. 5.11).

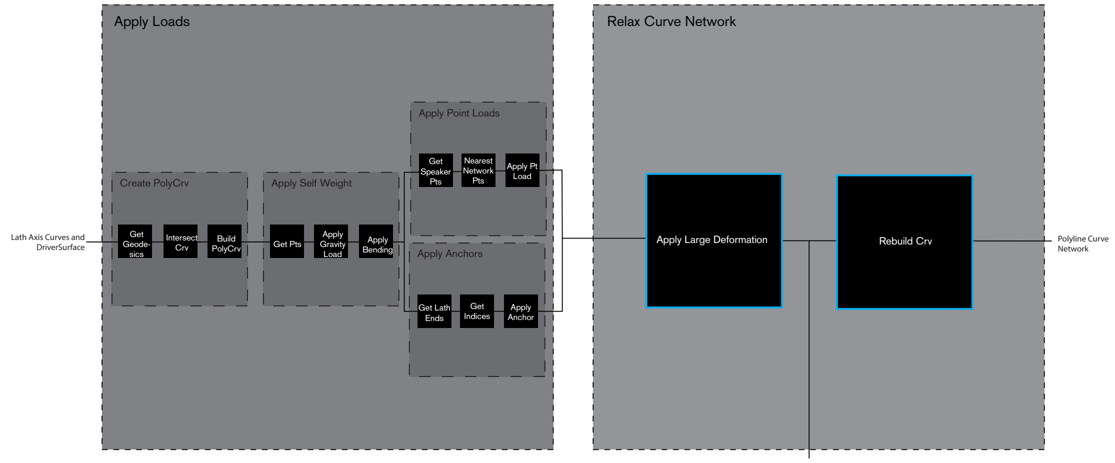

Fig 5.10 The workflow for developing the form of the gridshell from a setout surface to a funicular form, spanning two activities to applying loads and relax a network of curves.

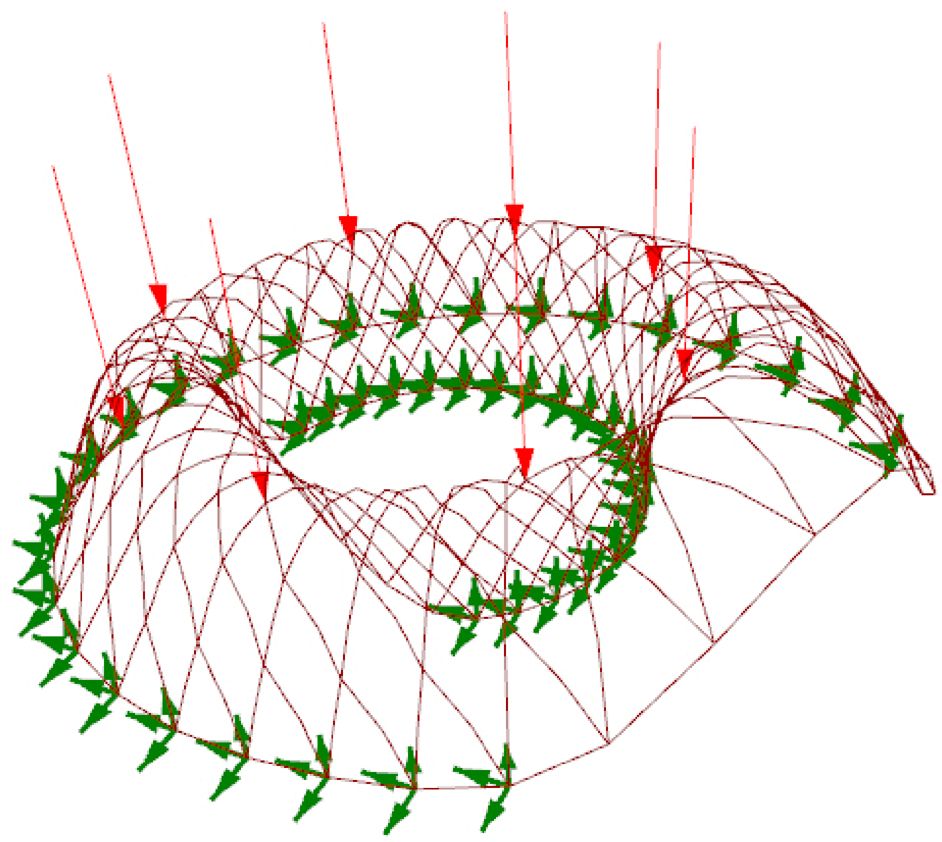

Fig 5.11. The digital model with loads applied to the curve network including point loads of speakers (red) and points along edges constrained in place (green).

Several plugins have been developed for Grasshopper which offer form-finding processes. Some, such as Daniel Piker's Kangaroo plugin are underpinned by simple engines which simulate networks of particles connected by springs. This approach has direct, though simple, parallels to the hanging models of Frei Otto (see Section 2.3.3). Working with Bollinger Grohmann's tools here, we used an alternative approach, calculating deflection through their *Karamba* plugin.

To use this tool, we represented our axis curves as polyines, with straight segments connecting nodes. We applied loads and then ran the Large Deformation routine which comes with Karamba. This was handled as a discrete Activity by the plugin. This simplicity, however, belies a large set of Functions being undertaken in parallel on each point, with individual loads applied locally at points. Through iteratively calculating deformation and moving this network of points, the shape of the network of polylines changes dynamically. With a sufficiently constrained example, the simulation finds a point of equilibrium. This linear workflow has a relatively high degree of modularity, with the Tasks for dynamic relaxation handled by discrete code modules.

5.2.3 Plugging Form-Finding into Analysis

Taking results from our form-finding simulations, we embarked on three parallel types of analysis (Fig. 5.12). We extended our use of the Karamba plugin to structural analysis. Tools such as this have been described as lightweight, providing rapid results from within the design software (Fischer, 2012). These results can readily feed back to drive subsequent iterations. While this analysis does not always have the rigour and accuracy of commercial tools, Karamba and others come with interfaces to export files to commercial tools for verification.

At regular intervals through the detailed design process, we analysed the performance of the structure for deflections and areas of high stress. We sorted local results taken across the structure to identify worst cases, likely areas of failure (Fig. 5.14). This workflow was designed and executed by Sascha and team, following a similar chain in Grasshopper across three Basic Tasks. Linking directly to the resulting

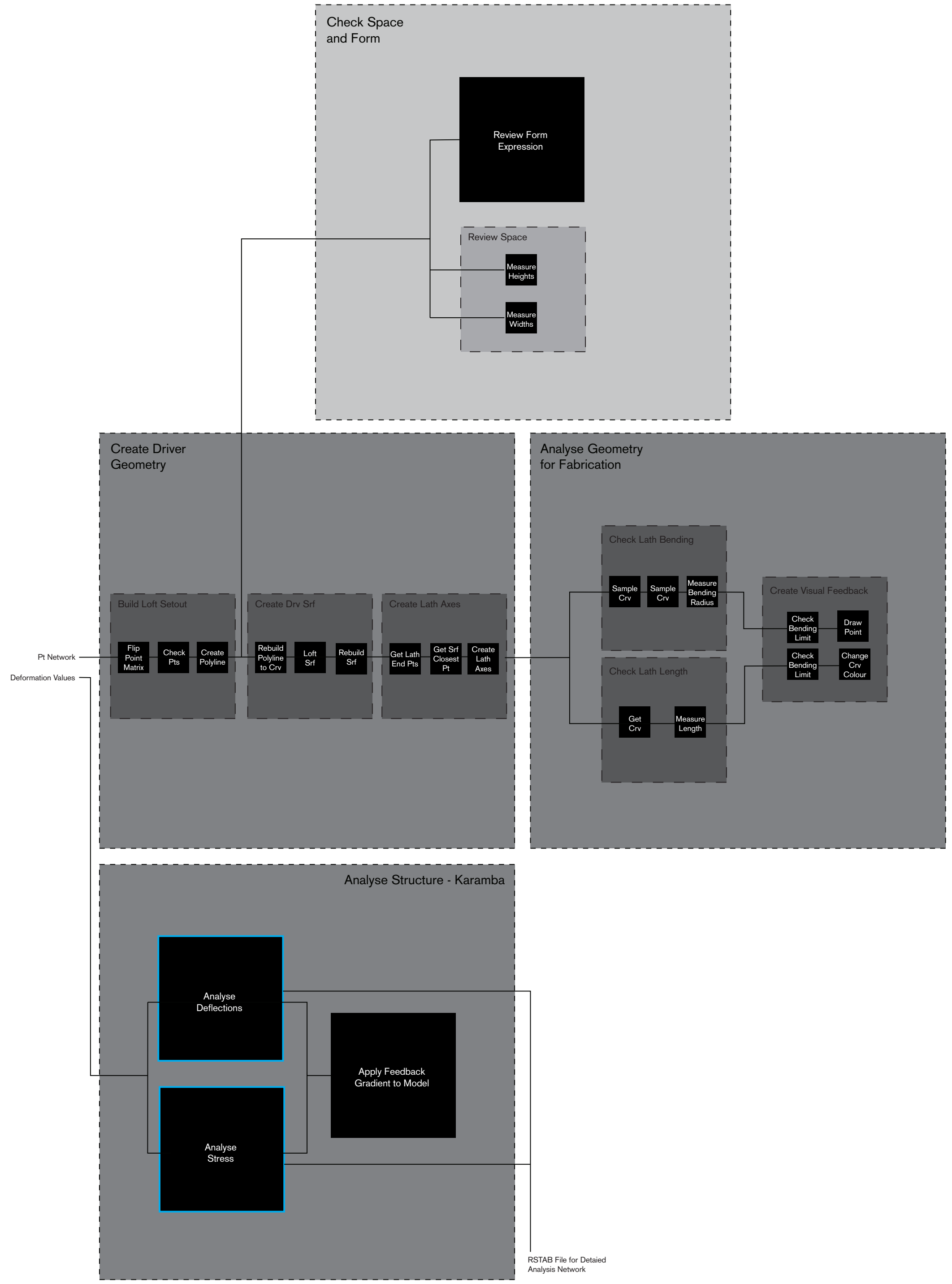

Fig 5.12. The parallel workflow for analysing for structure, material and space.

geometry from form-finding allowed us to incorporate this structural analysis into quick iteration cycles. We verified results using the structural analysis package *Dlubal RSTAB* for which *Karamba* exported native files. Further to this, members of Sascha's team used *RSTAB* for detailed analysis of stress within the proposed material. This Task branched from the main design workflow.

In parallel to structural analysis, we used a further parametric workflow to generate more detailed geometry of components in the proposed gridshell form. Taking the network of members generated through form-finding, we created a further control surface through a two-step process of interpolating curves through parallel points within the network, and then lofted a surface through these. We then needed to regenerate axes for laths of the gridshell, modelled as geodesic curves on this new driver surface. The Tasks of generating this geometry involved a series of approximate representations of existing geometry and we needed to control tolerances through this. We kept within nominal 20mm distances at each step but as with many such parametric arrangements, our workflow was difficult to control within these bounds.

With new curves representing lath axes, we could quickly analyse our designs in relation to fabrication constraints. Two geometric features were particularly significant, the overall length of laths and the bending radius at points along them. We identified maximum length with suppliers and appropriate bending limits identified through simple empirical tests (Fig 5.14). Through a series of Functions, we measured our curves and identified areas where a proposed form would not work. This relatively simple analysis was again part of a parametric schema, allowing us to automatically make checks in response to changes in form or in nominated material limits.

Our third analysis Activity centred on evaluating architectural qualities of a design. Some requirements were quantifiable, such as creating suitable clearances for the audience to walk through openings at key circulation points. The other Task of judging formal expression were qualitative and centred on decisions made by myself in conversation with various collaborators. I cannot break down this discursive process into finer process.

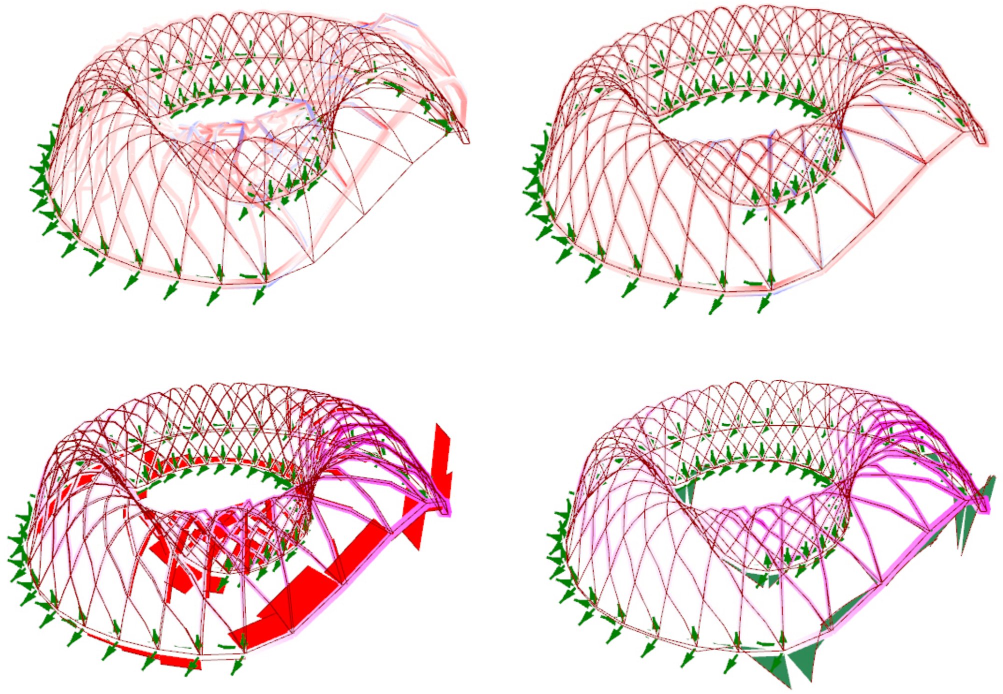

Fig 5.13. Images from the digital model showing a range of structural behaviours analysed with *Karamba*.

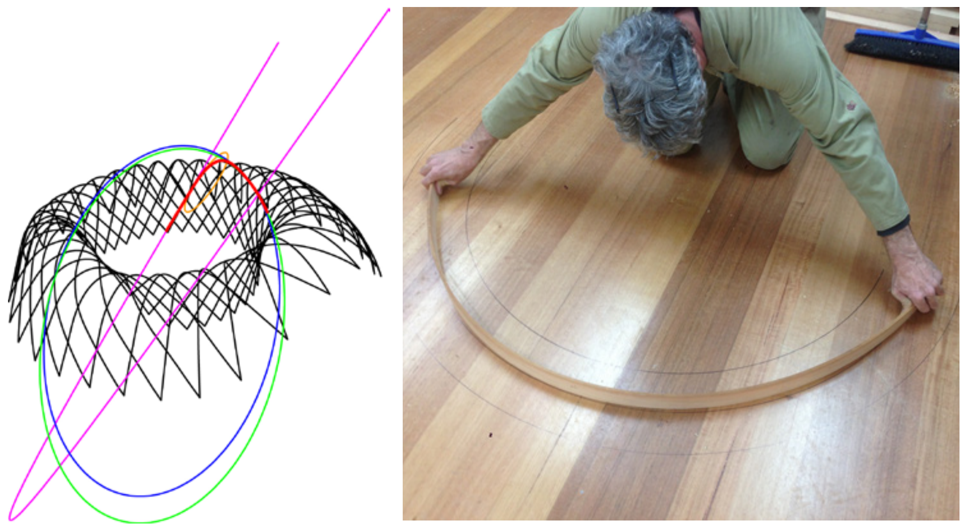

Fig 5.14. Analysing axes of laths for areas bending greater than a specified limit (left). Identifying a limit to bending laths through empirical testing (right).

5.2.4 Plugging Driver Geometry into Lath Fabrication

A further workflow extended from our form-finding process to generate information from our digital models to inform the fabrication of timber laths (Fig. 5.15). We used the detailed geometry of lath axes as a base for each of the 144 members in the detailed arrangement. We arranged laths in four layers with two running in each direction, with each layer on a surface offset parallel to the driver surface. Through a sequence of Functions, we created these offset surfaces and pulled laths to the relevant layers, thus producing parallel curves. We then split each axis curve where it intersected with those crossing it, and measuring the lengths of individual segments.

Through the design of fabrication details for the gridshell I collaborated closely with John Cherrey. Our design to fix laths where they overlap used simple, bolted connections. To fabricate each lath, we needed to drill holes at a series of points along their length. Using measurements of lath axes from our digital models, I creates a list of lengths between nodes. This again used a simple linear chain of Functions which provided us with a table of lengths for fabrication.

John was central to identifying a timber suitable to bending and available in lengths of up to six meters. He suggested Western Red Cedar and we tested samples before ordering blanks. John then created several jigs to control fabrication. These are exemplified by the simple device for routing slotted holes into laths (Fig. 5.16). This jig constrained the path of a router, allowing students without skills or experience with a router to accurately cut slotted holes. We tasked pairs of students with measuring and marking hole locations using the tables of lengths discussed above. A second pair then checked these measurements and, where correct routed holes using the jig. We offset the final measurement on each list to mark and cut the lath to the desired length. We finalised laths for installation by adding spacer blockers at centres between holes. These blocks held pairs of laths in parallel trajectories when bent in place (Fig. 5.17).

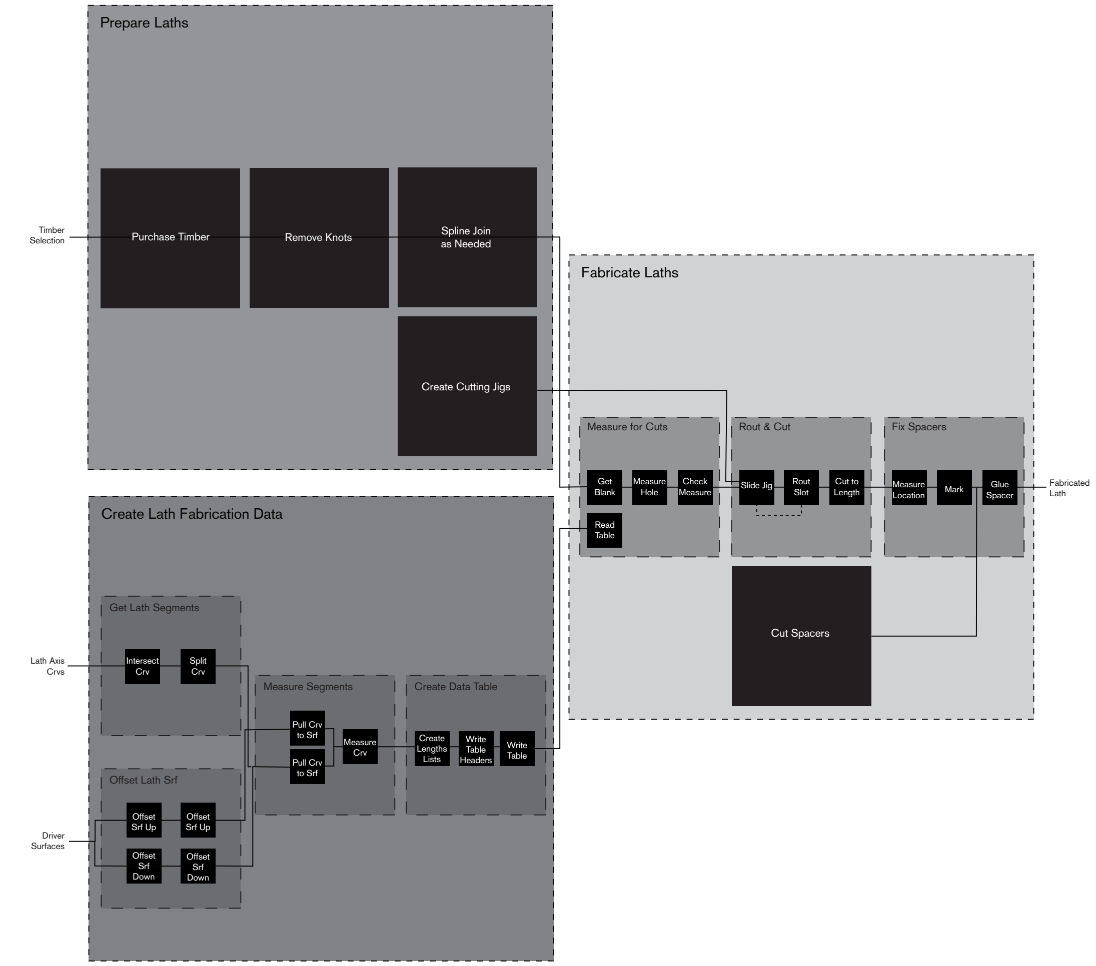

Fig 5.15. The workflow across Activities to fabricate laths from simple straight timber members.

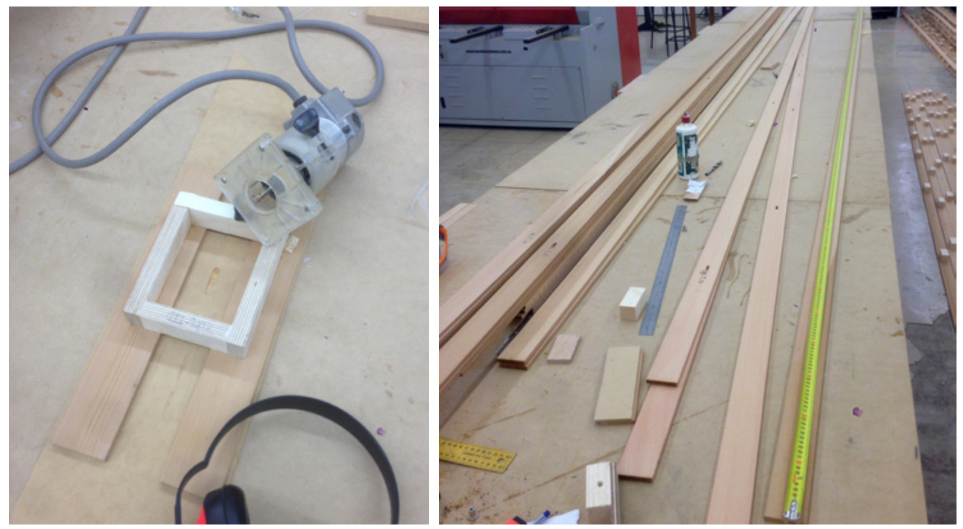

Fig 5.16. Routing slotted holes into laths with a simple jig (left). The jig was designed to simply slide along the blank (right), fixed at marked locations and then slots routed by hand.

5.2.5 Connecting Software Plugins to Fabricate Edge Beams

In contrast to the relatively simple extraction of tables of lengths to fabricate laths, fabricating edge beams required more complex transfer of information from digital models to material part. From a linear chain of Tasks in the digital models, the fabrication workflow required us to bring together three Tasks into another chain for assembly. Once again I worked closely with John Cherrey.

John and I designed edge beams as box sections which twisted around a central axis curve. We designed this as a consistent section around these curves, at any point oriented perpendicular to the tangent plane of the driver surface at its edge. Rather than model surfaces of these beams, we created a linear chain of Functions to model the edges of these beams. These were consistently offset along axes and twisted around the axis curve relative to the driver surface. A parametric modelling environment is well suited to quickly modelling this type of detail and I once again drove this through a *Grasshopper* model.

We then divided the curves for these beams into segments for prefabrication. We designed these to be fabricated from a thin plywood. We constrained segment sizes to within a 1200 x 2400mm frame in response to available sizes of both plywood sheets and a CNC router for fabrication. At each proposed joint in segments, I modelled a plane perpendicular to the central axis. I then split the edge curves with these planes, providing four curve segments to define the outside shape of each segment.

In place in the 3D model, I then lofted developable surfaces between rail curves. I then flattened these surfaces into planar shapes without distorting the shape of the part (Fig 5.19). Each face of each segment was unrolled. Continuing a linear chain of functions in a parametric Grasshopper model, we then used two software plugins for the Tasks of nesting parts and generating CNC machine programs (Fig 5.18). The *Rhinonest* plugin was used to arrange parts efficiently without tool collisions. The *RhinoCAM* plugin was then used to create machine files for 3-axis cutting. Using these commercial plugins, each task was modular and reliable. The CNC fabrication Activity

Fig 5.17. Routing slotted holes into laths with a simple jig (left). The jig was designed to simply slide along the blank (right), fixed at marked locations and then slots routed by hand.

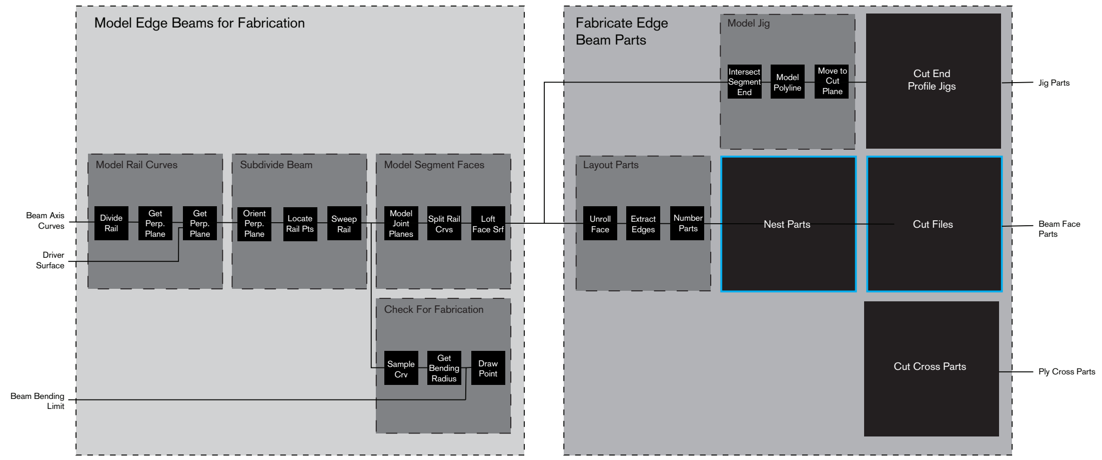

Fig 5.18. The workflow arrangement for fabricating parts and assembling segments of edge beams.

was outsourced to technicians running the 3-axis CNC router in the RMIT workshop.

Beyond the fabrication of these parts, it took several attempts for us to find a suitable technique to assemble beam segments. John Cherrey led this process, navigating challenges including inconsistency of bending in some plywood samples (Fig. 5.23). He also sought to discretely fix parts with glue rather than exposed mechanical fixings. As well as the te unique CNC-cut faces of each segment, a series of standard cross plates were fixed at regular intervals along the length of each segment. These stiffened up the assembly and helped to control tolerances. We further cut custom jigs with the router, each designed to hold a specific segment in a specific place during assembly.

We introduced jigs only after identifying errors in the shape of the assembled parts. Once complete, the shape of each segment was checked by measuring between a series of corner points and checking these back to the digital model. Through this Activity of assembling beam segments, we relied heavily on the skill of John and he had to closely execute a sequence of Functions to achieve acceptable results.

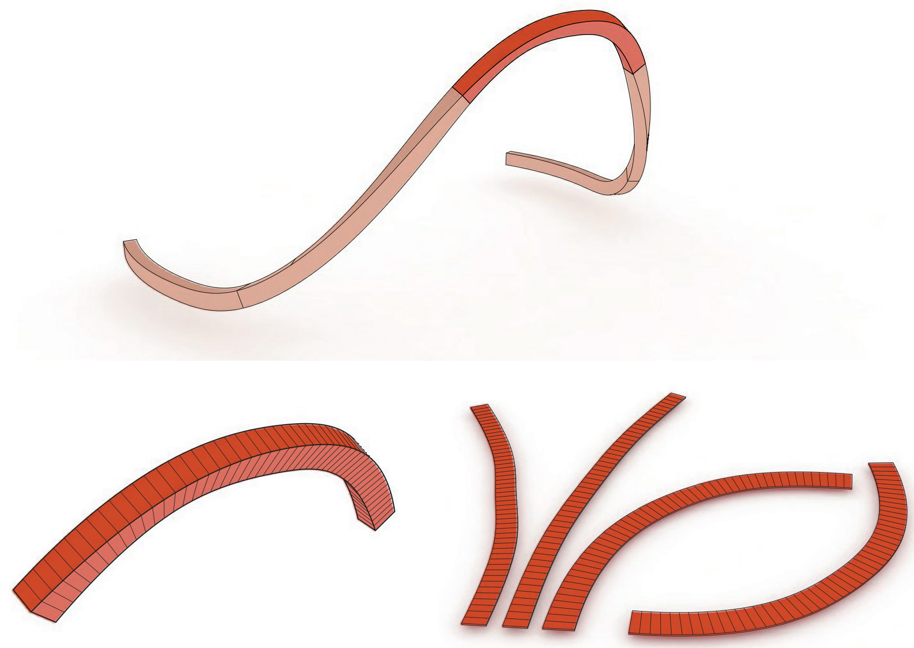

Fig 5.19. A diagram of a beam segment (top and left) and nested face parts for CNC cutting (right).

Fig 5.23. John Cherrey tests a jig to fabricate edge beam segments with bent plywood faces. The assembly of these segment parts required numerous tests to find a sucessful technique.

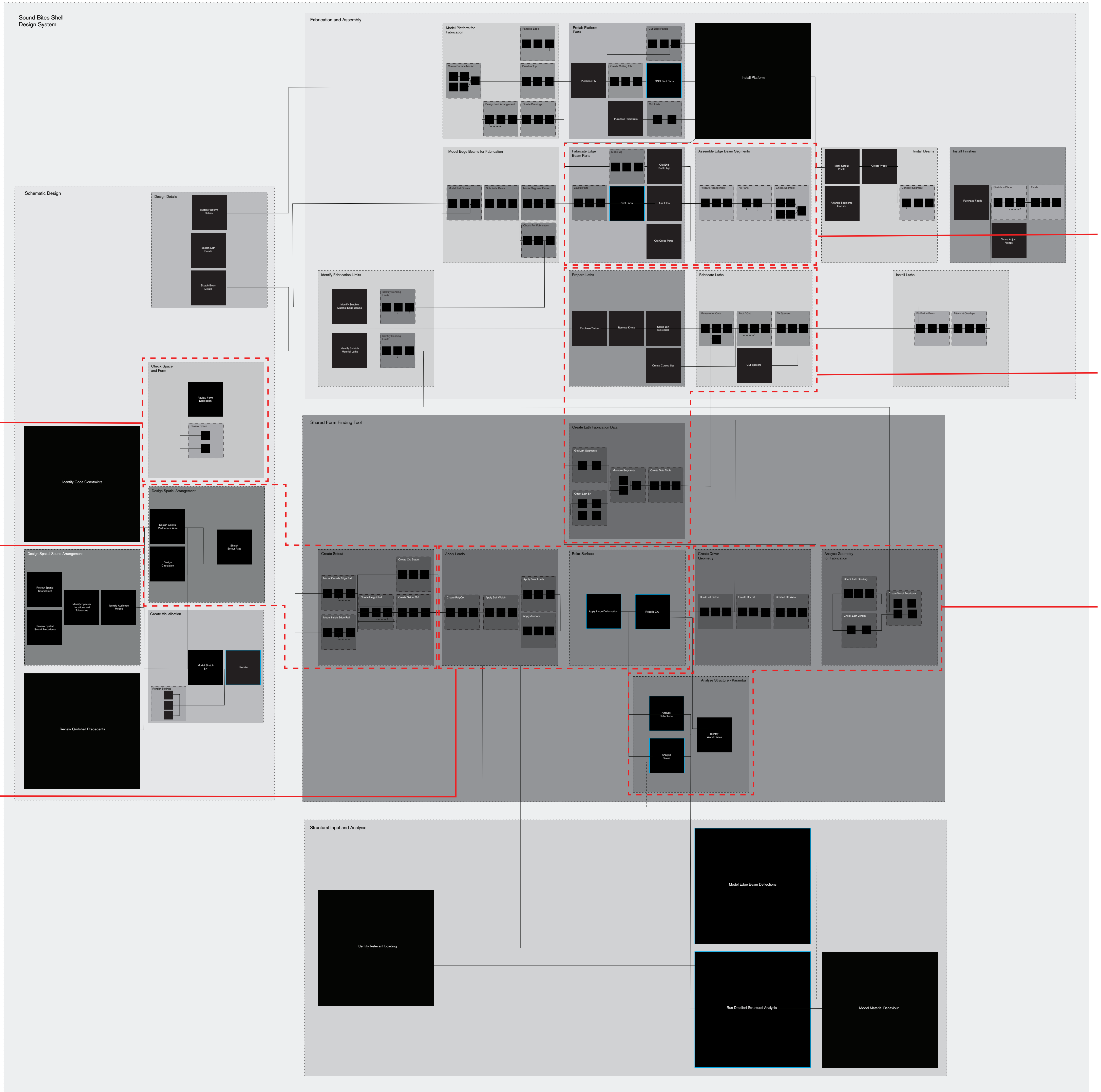

Fig 5.21. The Design System of the Sound Bites shell with divisions for form design, structural analysis, fabrication and form-finding.

5.3 The Sound Bites Design System

As with all projects, the workflows I have presented here have covered aspects of form, performance, material and fabrication. Here the research centred on the potential to not just make trade-offs between these but collaborate through shared design models. As I described earlier, shell structures are known for their form-finding processes in which dynamic simulations of material, structural loads and material are negotiated to find a stable state between the three.

Once again, the Divisions within the Design Systems have fuzzy boundaries, defined primarily through the expertise and leadership of an individual collaborator. This leadership was clear, as Sascha led structural analysis, John conceived and tested fabrication details and I produced schematic design arrangements. In this case, however, our form-finding led to the emergence of a fourth Division within the Design System. We interfaced the three other Divisions to this.

I have already discussed the intention for material and structural performance to drive design and this Division developed around shared digital models, allowing us to quickly share data and iterating rapidly through design options. This Division acted as the single converging element of the workflow. Form-finding simulations required input from each of the other Divisions: from formal design, the quantities and arrangements of laths and edge beam trajectories, from structural design the loadcases suitable for simulation, and from fabrication, the material bending limits for edge beam and laths. Together these helped define a starting condition for the dynamic relaxation routine.

This central Division follows a largely linear sequence of Functions and Tasks to create geometry and execute form-finding routines. While we worked at a relatively fine grain through this Division, it had a relatively high degree of modularity as the sequence and Tasks followed one another. At the end of a linear sequence of form-finding process were three analysis Activities which I discussed in 5.2.3. This analysis is closely coupled through parametric models and feedback thereby occurs over a broad scale. This allowed us to use material and structural performance to drive design

Fig 5.22. Assembling an edge beam segment. CNC cut faces were arranged in around square bracing plates, with all parts glue fixed and taped in place for curing.

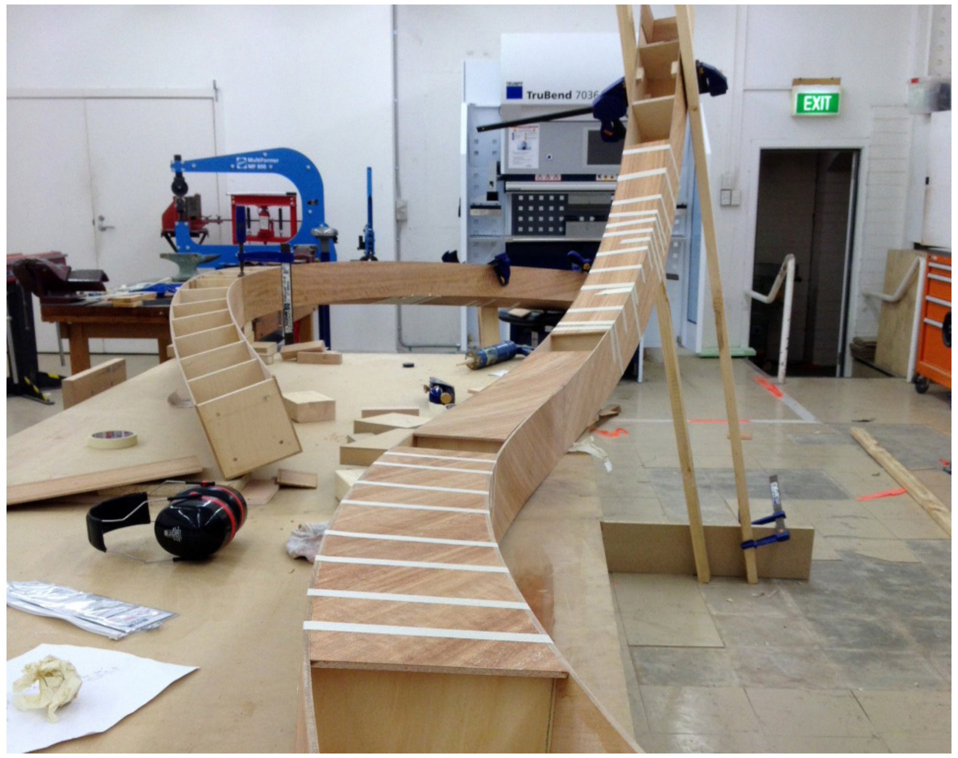

Fig 5.23. Preassembly of multiple segments to test connections and shape.

outcomes.

This feedback and iteration stands in contrast to a conventional, downstream flow of information in design and delivery. Such states of fabrication serving design occured elsewhere in the System, notably through the fabrication of edge beams (Fig. 5.22 & 5.23) and the construction of the central platform structure. I have already described the former, and the latter followed a simple workflow to design, fabricate and assemble parts. We conceived this platform as circular in plan and 600 mm high. We fed this design information downstream to fabrication where we specified a set of off-the-shelf floor joists arranged radially and with conventional timber flooring as an upper lining (Fig. 5.24). Drawings of this arrangement were used to procure parts and the platform was built by a team, independent to the gridshell team.

5.4 The Sound Bites Prototype

With a team including a class of students, we successfully designed and installed the full-scale prototype in the six-week period, in time for the exhibition opening (Fig. 5.25). The prototype includes 144 laths, bolted together in a network with over 1200 nodes. We produced 22 segments in the edge beams, themselves composed of numerous parts, and connecting continuously into the central platform. Our team also hit a series of interim deadlines for finalising gridshell design, procuring material and prefabricating parts.

As a prototype for design, the final installation resulted through much negotiation. We faced a number of challenges in driving deep connections between material limits, structural performance and providing for key spaces. These were resolved through many iterations, taking over 80 versions of setout geometry and loads before we could create a form in which laths were not bent too tightly, while at the same time providing circulation spaces which were sufficiently generous.

Our structural simulations produced some unexpected results, especially in

Fig 5.24. Assembling the plinth at the centre of the Torus. Parts were prefabricated and installed by an external team.

Fig 5.25. Installation of the edge beams and laths, with the inside beam connecting the platform. The interconnectedness of the structure meant that beams needed be propped until all laths were installed.

the apparent behaviour at the edges of the shell, at the major entry to the structure (Fig. 5.26). Some simulations suggested that the laths might in fact lift the edge beam in this area. After a series of detailed investigations, we came to a form which appeared relatively stable. The prototype proved this to be the case, with this beam segment dropping 5mm with the removal of the key prop which provided support through assembly.

As a prototype for production, fabrication of the laths proved straightforward. Our relatively unskilled workforce was able to measure and cut slots with out a single error among more than 1200 holes. As I have already mentioned, however, we encountered a series of challenges in prefabricating edge beam segments. The assembly of CNC cut parts, fixed in a range of complex curved shaped with glue and pins, required a high degree of input from John Cherrey (Fig. 5.23). His experience and skill were important to producing a relatively consistent result.

We undertook installation of the edge beams and laths over a 5-day period. Segments of beam were arranged on site, bolted together and propped where necessary. Regular checks of location of parts in space were made to ensure the structure would adequately connect. Laths were installed from the outside beam and connected to neighbours moving inwards. We bolted together layers of lath with spacer blocks to avoid collision and maintain a specific distance between layers. Parts were fabricated to allow for onsite adjustment through features such as slotted holes in laths. As more of the structure was assembled, we increasingly needed to adjust the previously installed parts to fit new. While the western red cedar laths proved sufficiently forgiving, this manual adjustment highlights that we need much further control if we were to consider further prototypes. Further detail on the collaborative design and prototyping process has been published (Williams, N. et.al., 2014).

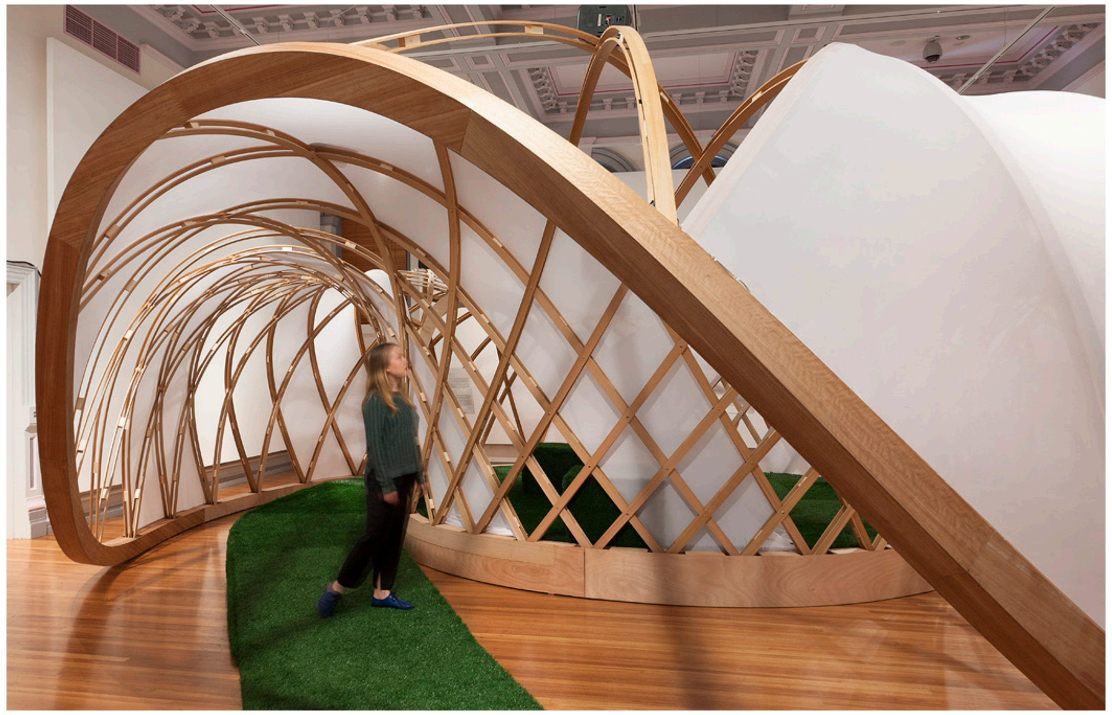

Fig 5.26. The installed structure with major entrance under the cantilevered edge beam.

Fig 5.27. Details of fixings between laths and a fabric cladding applied in select areas.

Fig 5.28. The central performance space of the Sound Bites Shell and views to the surrounding promenade.

MUSIC ROOM

Design & Fabrication:

Nicholas Williams, RMIT University & Upstream Studio

John Cherrey, School of Architecture and Design, RMIT University

Acoustic Design:

Prof Xiaojun Qui, Design Research Laboratory, RMIT University

Industry Partner:

Deutsche Schule Melbourne

Material Sponsorship:

Stora Enso

The project was supported by an 'Innovation Voucher', Department of State Development, Business and Innovation, State Government of Victoria.

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Brendan Knife

6.1 Music Room Background

6.1.1 Research Premise: Robotic Performance in Fabrication

Industrial robots have long been on the factory floors of manufacturing companies. They are today used in many industries as a flexible, tireless and precise workforce. The construction industry also has notable examples, with trials run in Japan from the 1970s onwards (Bock and Langenberg, 2014, 98). As this type of robots has become more affordable, they have recently received great interest from architects. This has added to and extended the discourse on the generative potential of digital fabrication for architecture (Gramazio et. al., 2014). More than other machines for digital fabrication, however, these robots have been celebrated by designers as performative in their movement, to the point of being likened to a ballet (Picon, 2014, 57).

Countering these perceptions are pragmatic limitations to utilising these robots. When compared to many other CNC machines, robots move more slowly, are harder to program, and are less dimensionally accurate. Many tasks can be more quickly and reliably undertaken with another type of machine. For example, to cut timber joinery, a gantry-based CNC machine is the common solution amongst leading fabricators. To date there are few direct and tangible examples of industrial robots in construction supply chains. This conflict reflects broader challenges throughout this research.

Amidst this tension, over the past decade a significant international community of researchers has grown around robotics in architecture, for example, through the association for Robots in Architecture. This community is applying these machines in a range of novel applications such as applying carbon strands to membranes (Fig. 6.01), to weaving material and to more conventional tasks such as milling and routing. This diversity of task is driven by their wide range of movement, the openness to apply multiple end effectors, and the ability to combine them with other equipment. As such, they have been described as generic machines, ready to be engaged as an active aspect of design (Menges and Schwinn, 2012, 121).

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Fig 6.01. Reseach into robotic fabrication by, for example, the Institute for Computational Design in Stuttgart is driving a broad community at the intersection of robotics and architecture.

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Fig 6.02. Robots combined with bandsaws for butchery (top) and in research for cutting stone.

6.1.2 Music Room Brief: A Space for Music Pedagogy

The teaching of music within primary and secondary schools has some widely accepted benefits. In Australian schools, however, there is a documented lack of spaces for teaching music (Lyons, 2013, 9). Finding suitable spaces is challenging, requiring both appropriate internal acoustics and good separation to provide acoustic privacy to adjacent classrooms. The Music Room research centres on this challenge, responding to a commission from a local school to develop a prototype teaching facility to be used and tested within an existing building on their campus.

Performing and practising music in large spaces such as concert halls has been widely researched. Small spaces, however, have received less attention, though strategies for the design of small music practice spaces have been outlined by Osman and Fricke (2003) and further by Riduan Osman (2010). Among the key issues they identify are:

- The proportions of a space should be designed so as to avoid reverberant modes. To achieve this, ratios between length, width and height are analysed.
- Preferred reverberation times are identified per instruments and per frequency. The primary means to shape this reverberation time is through varying materials and their proportional areas across the interior walls.
- The interior acoustic should be diffuse to avoid flutter echoes and specular reflections. Diffusers are a common sight in music performance spaces such as recording studios, providing variation to depth and shape of the wall.

Further to this are acoustic privacy concerns focused on airborne noise coming from instruments rather than impact vibrations. Common measures for airborne articulation are weighted Sound Reduction Index (Rw) and Sound Transmission Class (STC). In this case, an STC of 60 was identified as a suitable target level. This provides a high level of privacy, well above that in common buildings and was driven by the need to provide quiet teaching spaces, including a library, directly adjacent to the Music Room. Activities as sonically different as learning a trumpet and reading a book were to

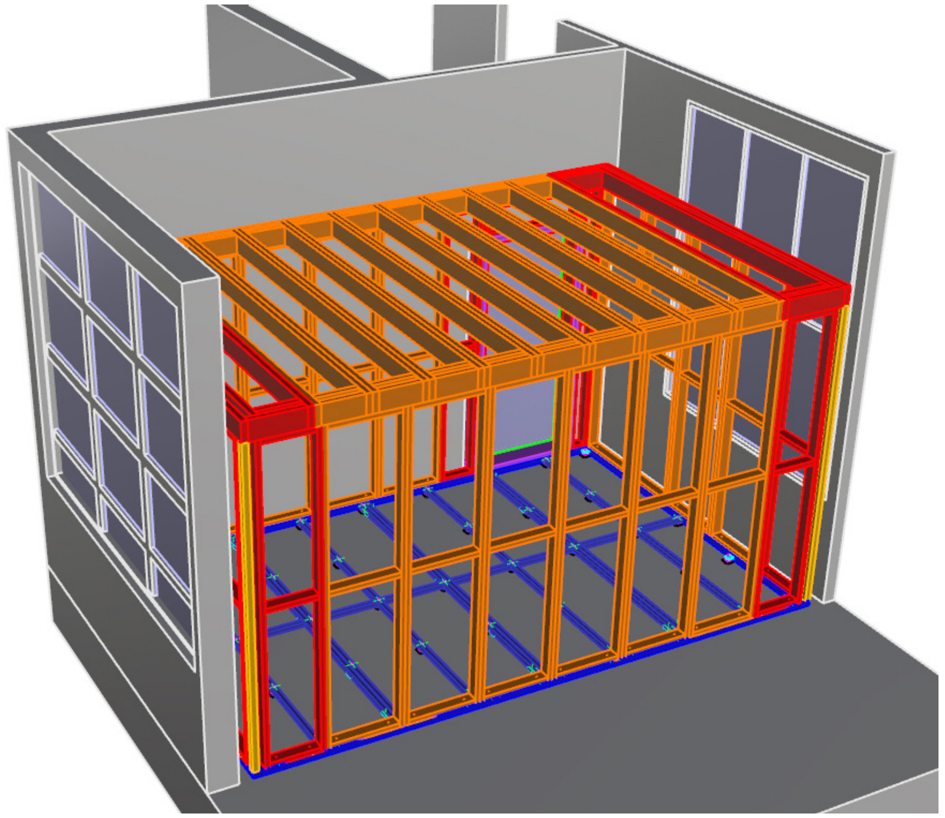

Fig 6.03. A rendering of the space for the Music Room with a timber frame designed to fill the space. While length and width were set, ceiling height was adjusted in response to testing of room modes.

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Table 6.01. Ideal reverberation times of small Music Room (Osman, 2010, 3).

be juxtaposed with only a single building partition between them.

Through early discussions with acoustics experts, we identified that sound transmission and interior acoustic articulation needed be treated separately. To create an acoustically private box we proposed a system of frames and panels to be prefabricated and on site. The room form was designed to maximise interior floor space on site, with the ceiling adjusted to avoid reverberant modes. We then turned our attention to the design of a system for the interior lining, with aspiration for a novel interior aesthetic and acoustic for the room.

6.1.3 Prototype Focus: Inventing Fabrication to Drive Design

Addressing precedent research in robotic fabrication we recognised both design opportunities and potential efficiencies in cutting material with a linear blade. In industry, robots are paired with bandsaws in a number of situations (Fig. 6.02). Contemporary butchery uses this combination for cutting up animal carcasses (Khodabbandehloo, 1993, 1). The Motoman company in Japan uses robots to undertake common cutting tasks for more common timber parts, ranging from stair stringers to guitar bodies (www.youtube.com/watch?v=M3rjmC8XTPo). The potential advantages of the robot in these cases are not in cutting difficult geometry but rather in controlling the trajectory and speed of the workpiece as it moves through the bandsaw blade.

In recent reserach by architects, a material blank has been moved with a robot arm through a blade to cut a curved surface shape. Exemplars include the use of a hot wire to cut foam (Feringa and Sonnegaard, 2014), a wire diamond blade to cut stone (Feringa, 2014) and a bandsaw blade to cut timber (Johns, 2014, Fig. 6.04). These researchers exploit the flexibility offered by industrial robotic arms to cut volumetric materials with the blade. The last example by Ryan Johns was intriguing for its use of timber, though Johns admits limitations in the freedom of cutting (2014, 22). These limitation fed into our design concept here.

Through conversation between myself and collaborator John Cherrey, we

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Fig 6.04. Johns and Foley (2014) develop a fabrication technique with a robot and bandsaw to cut timber, a similar combination of tools to the Music Room research.

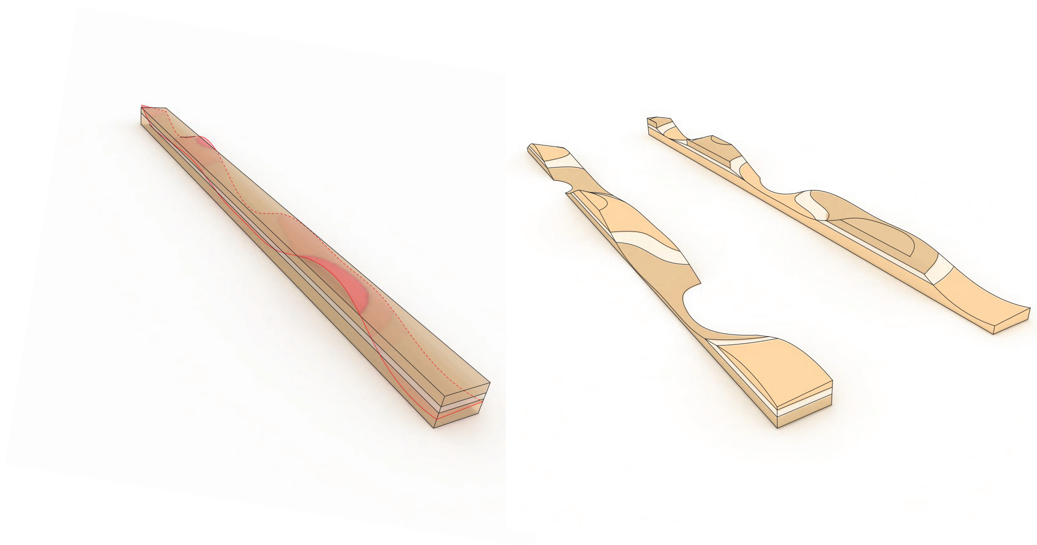


Fig 6.05. The concept for interior wall panels showing a rectilinear blank cut with a ruled surface (left), with both resulting parts showing profiles of material layering in the blanks (right).

proposed a design concept for a series of linear panels, cut from rectilinear blanks (Fig. 6.05). These blanks were to be cut with a ruled surface, the shape of which would be defined by rail curves running along the planar sides of the piece. Both parts of the cut blank could then be applied as wall panels with curved faces shown. Furthermore, through customising the blanks by using laminated layers of varied materials, curved profile shapes could be generated when cut, with multiple materials and finishes revealed.

6.2 Modularity in the Music Room Workflow

6.2.1 Plugging a Robot into a Parametric Model

The connection of design with robot occured through a parametric model created in *McNeel Grasshopper* and *Rhinoceros*. This model spans two Activities to generate and edit geometry, and to creating programs for the robot (Fig. 6.06). This process begins with a series of curves running in parallel planes which define the joints between adjacent panels. Between any two adjacent curves, we can generate the geometry of a ruled surface for a part, lofted through a series of ruling lines. A linear chain of Functions enables this, begun by dividing curves at discrete intervals. In parallel, we use this ruled surface to create further geometric elements, for example the intersections between the ruled cutting surface and layers of material in a part. Through this we can visualise the profile curves between proposed layers of material in a blank (Fig. 6.07).

Using this same Grasshopper model, we can analyse the ruled surface geometry to identify features such as the curvature of the surface in a given plane at a given point. This Task occurs in parallel to the generation of profile curves. It identifies the rate at which the surface curves around two planes, which I will later relate to a bandsaw blade. Arranging Functions in such parallel Tasks for manipulating geometry is straightforward in Grasshopper. I was able to quickly create a robust parametric model which related this geometric setout and analysis to a pair of input curves as drivers (Fig.

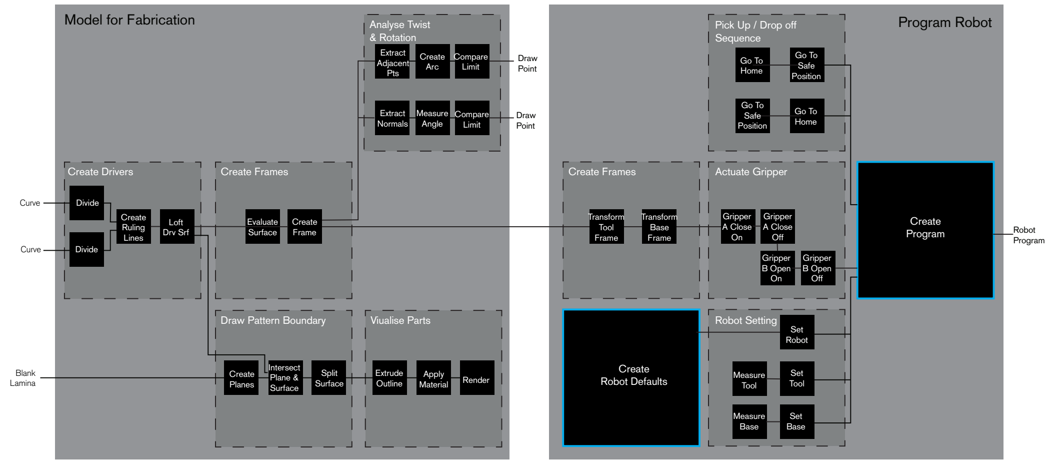


Fig 6.06. Two Activities of modelling detail for fabrication and using a software plugin to generate a program to run a robot.

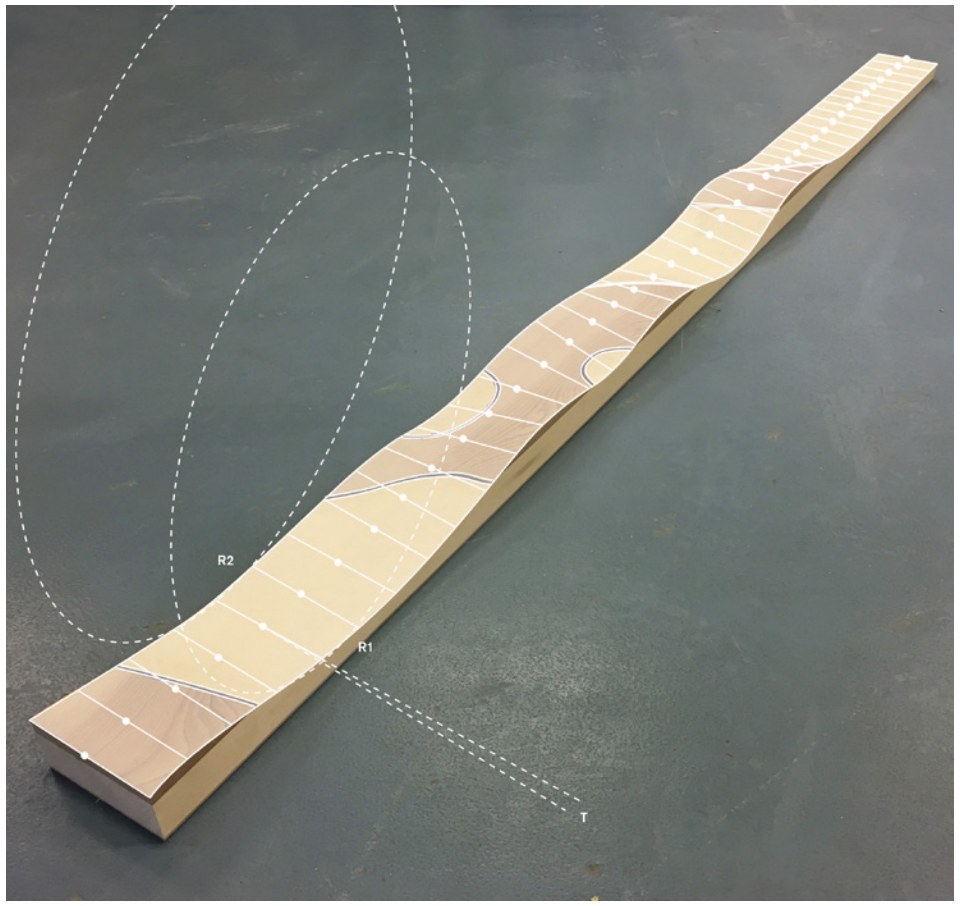


Fig 6.07. Geometry for details of the each panel including of ruling lines and surface and between two planar edge curves.

6.07).

Turning from detailed geometry to fabrication, I extended the Grasshopper model to define a trajectory for a part to move through a linear blade and following the ruled surface. I arranged a linear sequence of Functions to define planes parallel to the ruling surface and perpendicular to the original driver curves. In parallel I defined a further reference plane on the volume of where the part will be connected to the robot end-effector. Using the planes from the ruling surface, I then located this connection relative to a series of steps along the cutting surface, creating a trajectory for the robot to move. I completed this trajectory by adding further points for safely picking up and dropping off a part in a given sequence.

We then need to translate this trajectory into a program to drive a robot, covering three Tasks:

- Identifying the dimension of the robot and specific limitations.
- Creating a program file with specific information to interface with the robot.
- Translating the tool trajectory to rotations of axes on the robot.

Rather than develop workflows from scratch, I instead utilised the *Kuka PRC* plugin for Grasshopper. This plugin offers functionality which covered the first two Tasks listed above. Information regarding the robot at RMIT was captured and implemented by Johannes Braumann, the plugin's creator. I could use the plugin to further create a program to drive for the robot, relative to the trajectory I have described here. The final Task of translating the robot program to drive the six rotary axes and one linear axis is handled internally by the robot (Fig. 6.08). As such, we needed to test tool paths to ensure that we avoided geometric singularities or other errors. We further needed to check that we avoided collisions between the robot, bandsaw and walls. The *PRC* plugin provides visualisation which we used as a first pass before further verifying our results with the robot.

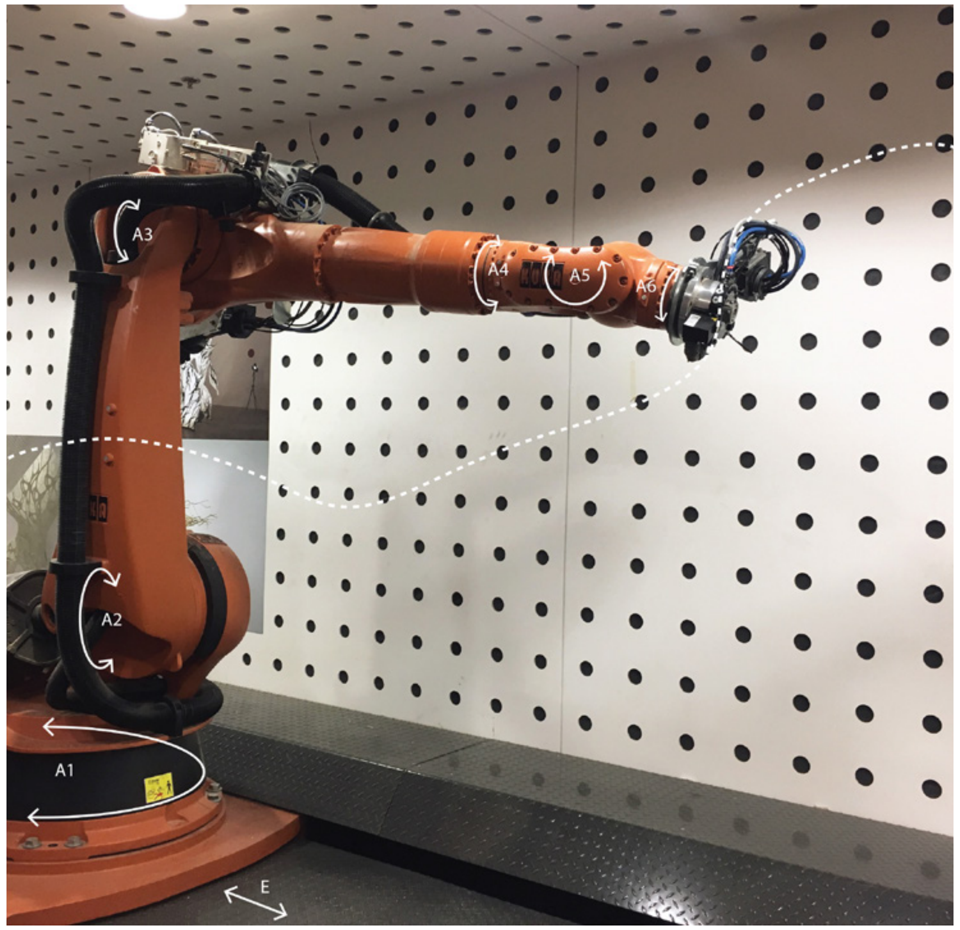


Fig 6.08. The robot with rotation axes highlighted.

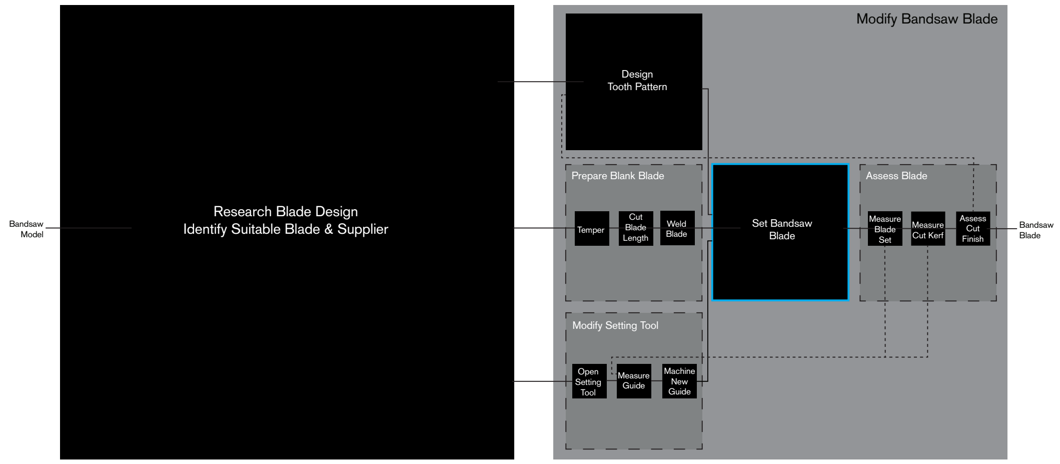


Fig 6.09. The workflow across two Activities for purchasing and modifying bandsaw blades. The first was undertaken by John Cherrey, the second followed a series of shared Functions and Tasks.

6.2.2 Plugging Craft Knowledge Into Technology

I have already mentioned the other machine used for fabrication, a conventional bandsaw. We salvaged a reliable machine which was due to be decommisioned but which was suitable for a broad range of bandsaw blades. We then set about identifying an appropriate blade. This was a key Activity for which I relied on the experience of collaborator John Cherrey, who has both used and designed many blades. We sought initially to maximise the flexibility in our cut forms and John set out to identify key suppliers with blades suitable for cutting curved, ruled-surfaces. The detail of this Activity was largely unknown to me. Nevertheless, John identified a spiral blade which seemed suitable and we purchased one for testing.

Our first test of the blade in combination with the robot was to cut a sample piece of 600mm in length. At this point, the relatively straightforward progress of our research quickly came to a halt as the test proved a failure. We identified a series of problems, including significant friction and burning during cutting caused by material becoming stuck in the blade (Fig. 6.10). Despite assurances from the manufaccturer, the blade was poorly suited to cutting materials as soft as timber. Furthermore, the narrowness of the blade meant that it distorted easily under load. As a result, we could only cut at slow speeds, the test taking some 20 minutes to cut the part. We realised that this pace was unsuitable for the job.

We returned to the Activity of finding a suitable blade, looking this time at more conventional blades. John soon discovered a relatively narrow set of options. In order to maximise the rate of curvature when cutting, we needed a blade with a wide kerf. such blades are not readily available, however, as blades are designed almost exclusively to have narrow kerfs in order to minimise waste. As we could not find a suitable blade, we realised that we needed to identify one which could be modified. This modification to achieved a wider kerf needed to be acheived without diminishing the quality of cut finish.

Led by John, we undertook an extended, iterative process of modifying and testing blades. We purchased several blades with a consistent depth of 12mm and

Fig 6.10. The first sample cut using the spiralled blade with visible burning to the cut face.

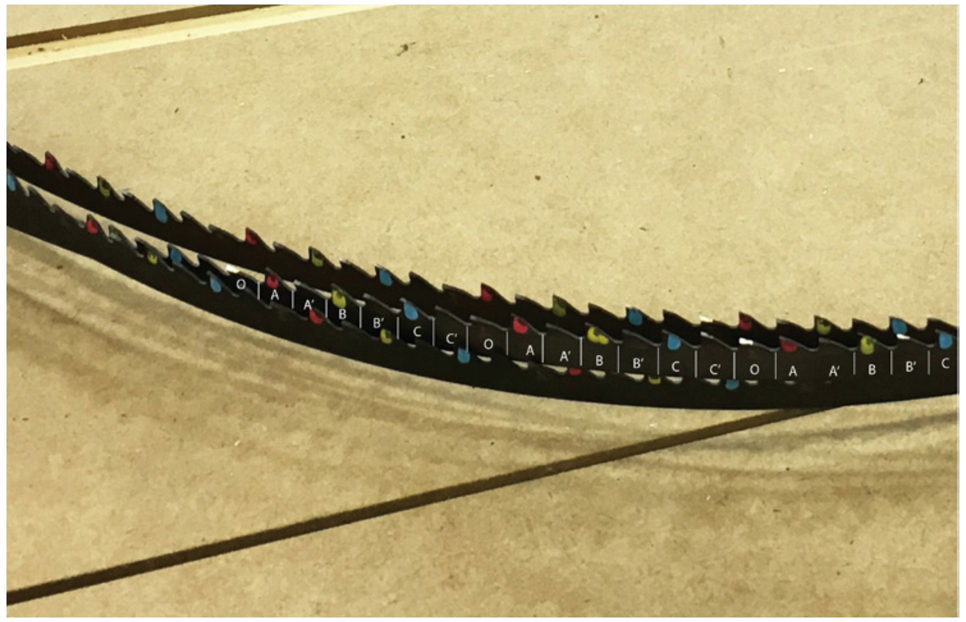


Fig 6.11. A custom set bandsaw blade. The blade was tempered and set to a pattern with teeth set to spcific angles.

large gullet, and then worked through a process of setting teeth in a suitable pattern (Fig. 6.11). This involved a sequence of Tasks and Functions to prepare the metal and setting tools. Test cuts using the robot were used to verify the limits of curvature and the quality of cut from each blade design. Through extensive tests, we identified a limit to twist around the blade, proportional to the depth of blade, width of piece being cut, and kerf of the blade. Where twist limits are reached, the blades distorts to create a so-called "washboard" effect, an effect regarded in literature as an error but which holds design potential for applications such as wall panels.

6.2.3 Plugging in Industry for a Custom Tool

Through a third, parallel series of Activities, we needed to design and fabricate an end effector for the robot. We had used a simple vacuum gripper through testing, which proved to be a suitable solution for relatively short parts up to 600mm in length. We recognised that to cut longer parts and to cut these quickly, however, would involve much larger loads and would require that parts be gripped mechanically.

We approached an engineering company to work with us to create a suitable end effector. This process required us to prepare a brief, specifying limits in the size of parts, geometric limits required to avoid collisions between blade and end effector when rotating parts, and details of the robot related to interfacing. The company took this brief and developed it, helping to add detail where needed. They provided a series of suggestions for available parts and product which could provide required functionality and through discussion design with selected parts was approved. As such, the design of the end effector centred a linear series of Tasks with loops to iterate and refine the design and selection of components (Fig. 6.12).

The final design of the end-effector is composed of a series of finger grippers which, when actuated, rotate and move to clamp a part in place. Pairs of these grippers are mounted along an aluminium extrusion which acts as a boom (Fig. 6.14). We can move the grippers along the boom and we spaced them so that their arcs of movement did not overlap. This was a key feature needed for a cutting sequence, providing us with

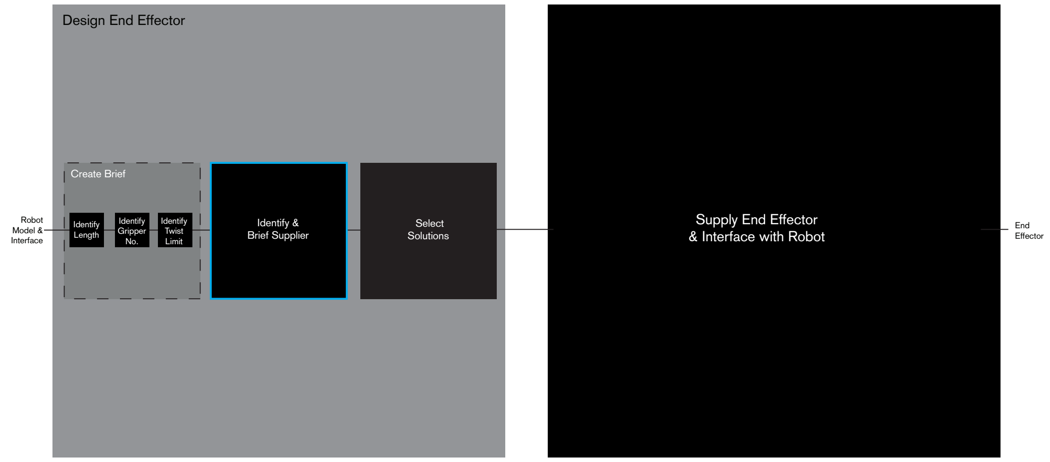


Fig 6.12. Two Activities to design, fabricated and install the custom end-effector.

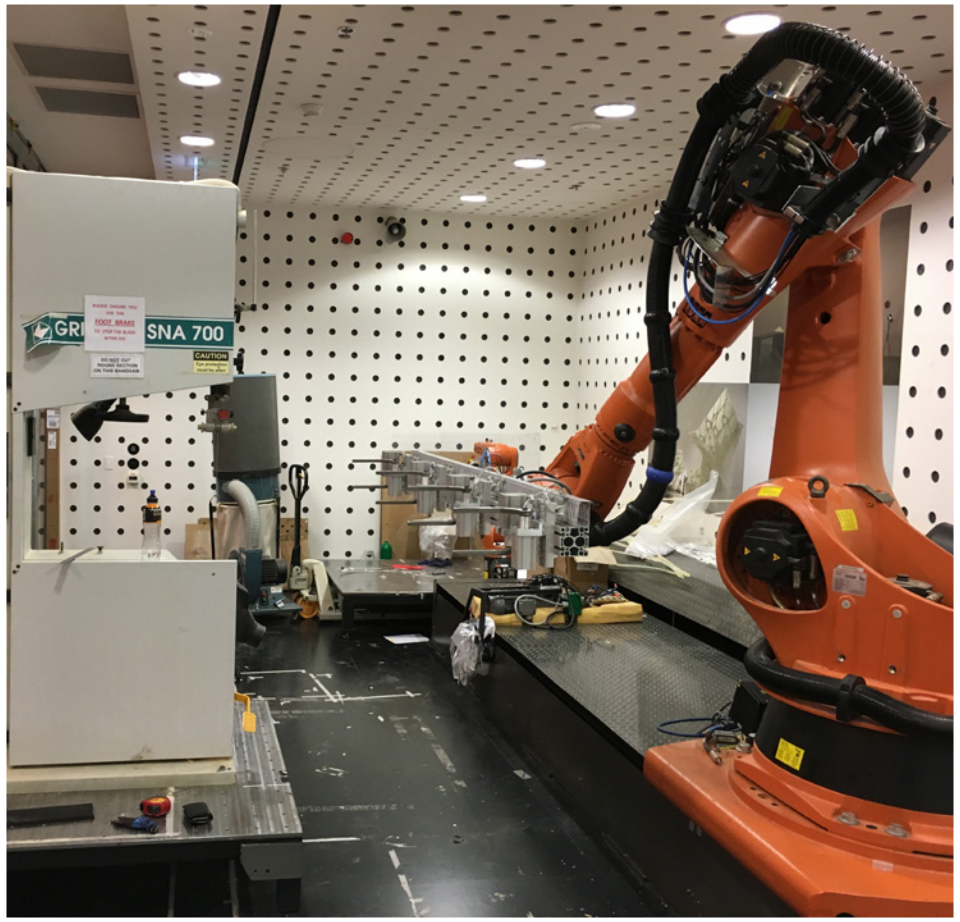


Fig 6.13. The bandsaw and robot with custom designed end effector featuring pneumatic "finger" clamps to hold parts for fabrication and retract as they pass by the bandsaw blade.

areas where one pair can close and another open without hitting the bandsaw blade. A standard plate for mounting an end effector was mounted to the back of the boom and provided a standard tool interface to the robot.

Our industry supplier drove the manufacture and mounting of the tool. My input was needed to support interfacing of the tool and the robot, through both hardware, to connect pneumatics to actuate the clamps, and through implementing software interfaces to program the actuation of the tool. The end-effector included electronic switching gear which split existing air lines into multiple channels. Working with our supplier, we then mapped these channels to digital signals in the robot control, providing a series of custom commands which we could include in a pragram.

To complete the installation we undertook two Tasks composed of looped Functions to calibrate precise location of a part gripped by the tool. First, we manually adjusted air pressure to checked the speed and pressure in the movement of finger clamps. When this was seemingly balanced and movement was reliable, we then adjusted the software definition of the robot's tool plane. This allowed us to control minor rotations of the tool, relative to the bandsaw blade. Gripping a 2.4m long part, rotations of one-tenth of a degree effected the precision at the end of a part by 3-4mm.

6.2.4 Plugging in Local Suppliers for Custom Blanks

A fourth line of parallel workflow for designing wall panels centred on the creation of custom material blanks. After testing of many blades and looking at our available budget, John Cherrey and I identified that timber would the primary material, being easily cut and cheaply available. We contacted several suppliers to discuss available stock. Rather than prepare a strict brief our enquiries were exploratory, seeking opportunities amidst a diverse set of available products.

With a tight budget and a desire to minimise waste, sizes of timber were critical. Our search drew on John's experience of standard sizes from local saw mills, alongside further ranges of imported timber. After some negotiation, we agreed upon

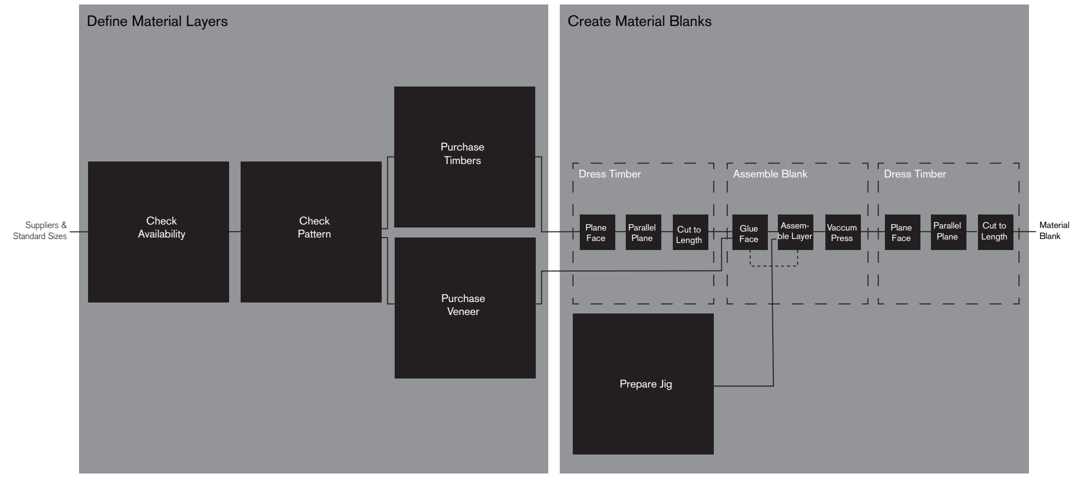


Fig 6.14. Two Activities to source and prepare timber, and to fabricate timber blanks.

Fig 6.15 The linear chain of manufacture and installation activities to deliver a suitable robot end effector.

two cedars to provide a base, a blonde ‘Alaskan’ cedar and a darker, Western Red cedar. Both were available in 150mm wide boards, a size to which we could further add layers of veneer in standard sizes. This width also aligned well with our curved cutting technique.

With timber to hand, the Activity of making blanks followed a linear series of manual functions to dress and size pieces (Fig 6.15). We completed this Task in parallel for each type of timber to prepare pieces for lamination. These parts then converged to the Task of laminating pieces into blanks. Again, this converged to a linear set of Functions, as we applied glue to each part and these then arranged them in layers. We used a vacuum table with membrane to apply pressure to parts as the glue set, over a minimum period of two hours. With rough, laminated parts to hand, we then finished these through a final Task of dressing them to size (Fig 6.16).

For final fabrication, we noted that the colour of the Western Red Cedar was particularly varied across the blanks. We paid attention to this and identified bookmatched pairs, arranging them in consecutive blanks to provide a level of visual continuity in the finished wall pattern.

6.2.5 Plugging In Sound for a Generative Design Process

As I have touched upon in the preceeding sections, our design approach to the form and pattern running across the interior panels responded to both acoustics and fabrication technique. I have already outlined four aspects of fabrication which directly informed the design across the ruled surface shapes of panels, and the quantities of each material exposed as finishes through cutting. Each of these aspects also affects acoustics. As with the FabPod discussed earlier, we sought walls which were non-parallel and aperiodic in articulation. The surface area of each material also directly contributes to the reverberation time of the space.

We were supported in acoustic design by Prof. Xiaojun Qui. He assisted initially to identify suitable reverberation times and room proportions, as oulined earlier

Fig 6.16. Timber being glue laminated under vaccuum press and rubber membrane.

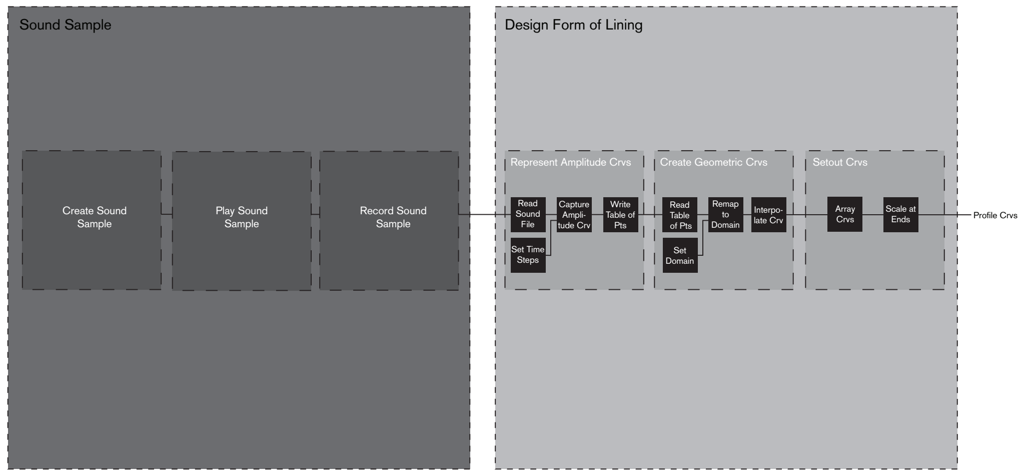


Fig 6.17. The setting out of driver curvedgeometry across two Activities to capture data from audio samples and to subsequently create and arrange curves in a 3D model.

(section 6.1.2). At the scale of wall articulation, he did not specify specific targets for each type of timber or specifics, nor targets for curvature rates and shapes. Rather, he indicated that at the scale of articulation which we could achieve with our fabrication technique, a broad range of curved form would be suitable. As a result, our primary drivers for the detailed design of walls were strictly architectural considerations of form and pattern.

Earlier I described that the geometry of wall forms was generated from a series of parallel, planar curves. We positioned these curves at gaps between panels, with each panel defined by two adjacent curves. With this system in place and panel widths determined by available timber, we considered a series of approaches to generate wall patterns. Through a workshop with students we explored over twenty techniques - from algorithms which recursively divided curves, to mapping a curve profile based on an image. While this exercise had some good pedagogical outcomes, this litany of digital techniques did produce particularly surprising or novel results.

We turned our attention to potential to plug in music software to generate pattern. We created a linear chain of software to manage a series of Activities to transform data from sound files into geometry. Our design workflow (Fig. 6.17) began with an Activity to generate and capture amplitude curves at regular time intervals. We abstracted these curves as comma-separated files, representing each as a series of points through which we subsequently interpolated a curve. We then plugged these files into a Grasshopper model, created curves, and then arranged these at relevant spacing along a length of wall (Fig. 6.19).

After numerous experiments, we settled on a sound sample of a tuning harmonics. Using our workflow we could easily connect through the geometric model in *Rhinoceros*. We could, in turn, plug this into the Activities which created detailed geometry for fabrication (section 6.2.1). As such we could move from sound sample to identifying fabrication problems in a matter of seconds. This allowed us to rapidly explore design options and find a desirable pattern.

Fig 6.18. Early digital studies looking at patterns generated by using the relief through multiple layers of material. We considered implications of symmetry and colour before settling on a final pallette.

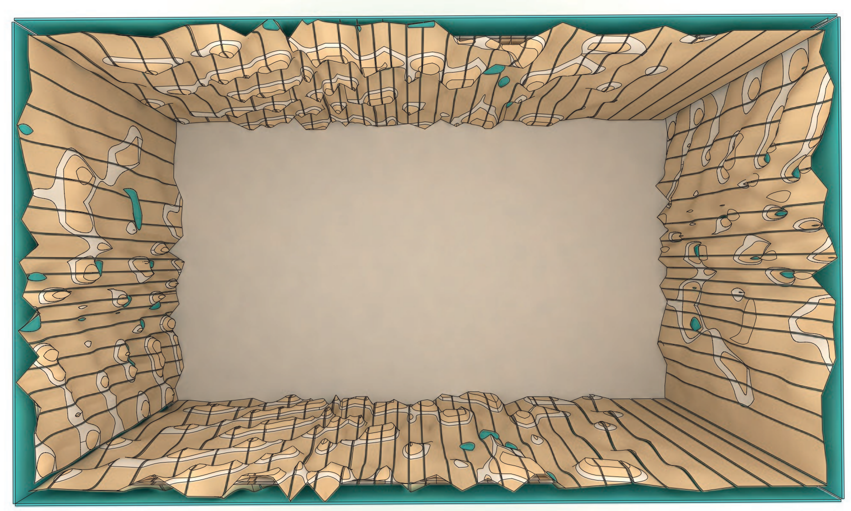
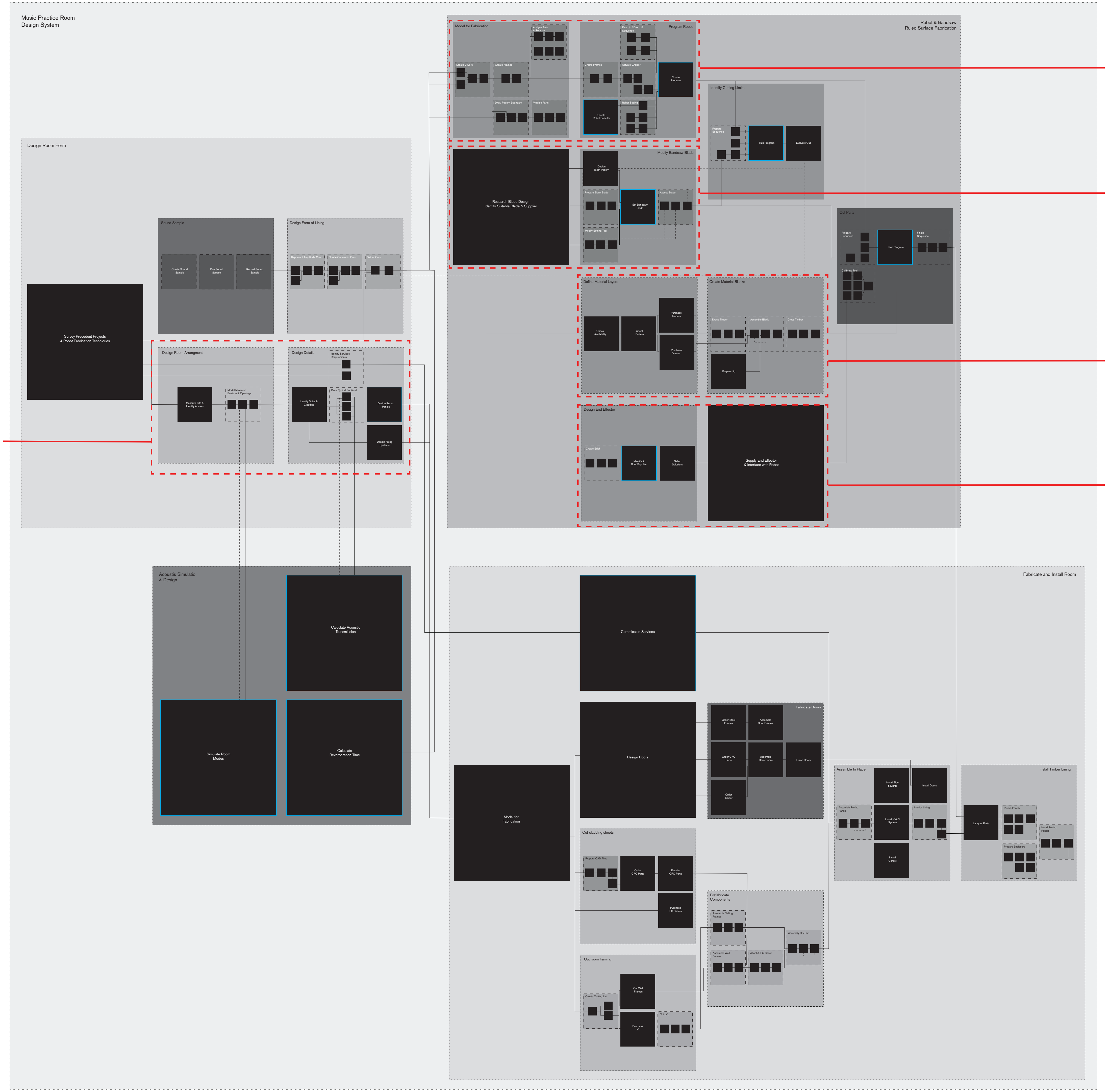


Fig 6.19. an aerial perspective showing the intended layout of a sample patterns of panels.



Modelling fabrication geometry and plugging this into a robot, Fig. 6.06.

Sourcing and modifying bandsaw blades, Fig. 6.09.

Procuring timber and fabricating blanks, Fig. 6.12.

Modelling fabrication geometry and plugging this into a robot, Fig. 6.14.

Capturing data from audio samples and generating geometry from this, Fig. 6.17.

Fig 6.20. The Design System of the Music, showing four Divisions including two for fabrication of the room shell and interior lining.

6.3 The Music Room Design System

Much of the discussion of modularity above focusses on the Activities to design a fabrication technique for interior timber panels. Within the broader Design System for the Music Room (Fig. 6.20), these four chains ran in parallel and converged in a final activitiy to fabricate panels. In contrast to other Systems here, this has two parallel Divisions capturing fabrication of the room enclosure and internal lining. This pair of Divisions addressing fabrication reflects the independence of the base shell and interior lining, both in process and in built outcome. Alongside these are Divisions for formal design and acoustic simulation, again reflecting activity and key expertise leading them.

Once again, there are clear ways in which fabrication and performance drove the design of form. The parallel development of the four aspects related to the robotic fabrication was necessitated by the dependency of each process upon others. For example, the curved surfaces to be cut are actuated through the toolpath of the robot. and constrained in two planes by the width of the material blanks and kerf of the bandsaw blade. We could only identify these limits through combining blade and robot to cut a specific shape into a sample part. Furthermore, the combination of material, bandsaw blade and cutting speed affected the quality of cut finish. Negotiating these interdependent activities to achieve an acceptable outcome required significant trial and error and the cutting process was developed to a relatively high degree of modularity within this division.

We passed feedback from robotic fabrication to the design of form through geometric limits to the curvature rates which could be successfully cut. This allowed us to avoid areas where limits were exceeded and to drive further curvature in other areas. Through extensive testing, we identified the geometric limits at which the bandsaw blade would deflect. Quantifying these as a ratio between rotation per 100mm of travel and the width of the part being cut, we were able to produce a washboarding effect at the cutting surface. This occurs where the back of the blade catches the material, deflecting locally. We produced a series of parts to control this effect.

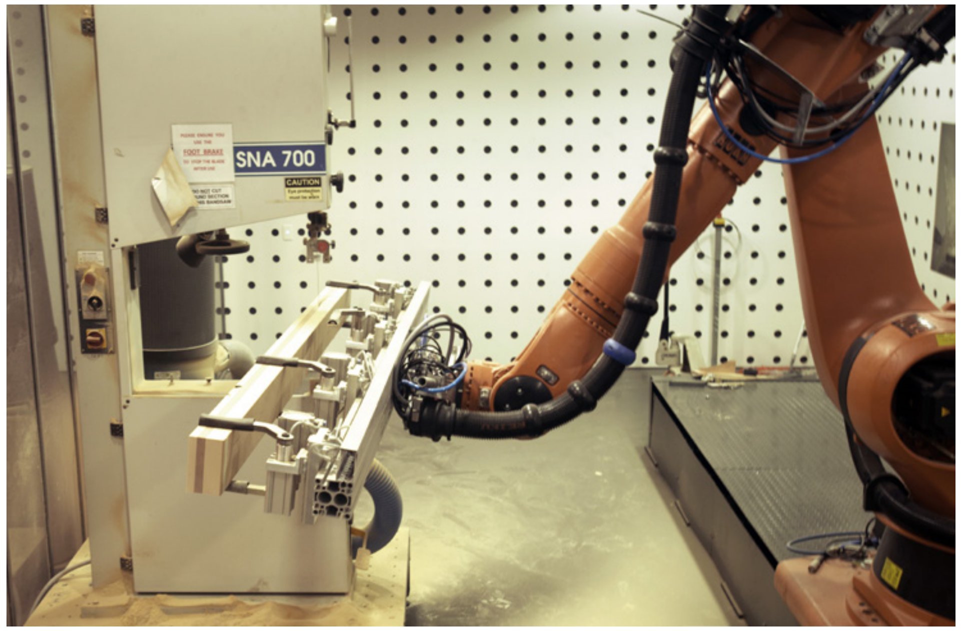


Fig. 6.21. The final fabrication process with robot guiding a timber part through the bandsaw.

Fig 6.22. The washboarding effect on the cut surface of a piece occurs where the twisting action through the blade reaches a limit to deflect the blade.

I established several interfaces to underpin connections between robotic fabrication and other Divisions. I have already introduced the set of planar curves generated through design, connecting through to the parametric model for fabrication and robot cutting. Flexibility in the shape and arrangement of these curves allowed us to design wall patterns in parallel to the fabrication technique.

We also established interfaces to a team focussing on acoustic performance, led by collaborator Prof. Xiaojun Qui. His team were engaged in early design discussions and we identified simulations to address independently the reverberation time of the interior space and acoustic attention of the enclosure. We suppllied them with 3D models and data on materials to support this, as well as drawings showing typical sections to help calculate the attenuation of the enclosure. As such, this feedback on performance helped to guide design improvements, though it followed a largely conventional process of design review.

Aspects of fabrication also served design here, most clearly in the delivery of the enclosing room. A system of prefabricated panels was designed, and the workflow followed a downstream flow of converging Tasks. Framing was fabricated, with a series of steel frames designed and ordered for the floor, and timber used for wall and ceiling components. In parallel to this, cladding panels were cut to size. Components were assembled, with sizes suitable for handling by two people. All components were then assembled on site in sequence, though a low degree of modularity in these Activities caused some mistakes and inefficiencies when assembling the panels.

6.4 The Music Room Prototype

The full breadth of work on the Music Room extended across almost three years, and split over three distinct phases. Initial design and fabrication of the room enclosure was completed within six months. We undertook prefabrication of panels in a University workshop, with some components supplied already cut to size. On site, steel floor frames laid first, followed by wall panels (Fig. 6.25). We arranged cladding panels in a staggered fashion, overlapping at corners to similarly minimise sound transmission

Fig. 6.23. A group of adjacent panels checked for tolerance once cut. Both sides of each part were used and applied as panel on opposite walls.

Fig 6.24. Panels mounted to battens are laid in matching pairs and prepared for transport.

in these potentially weak areas. We also extruded a synthetic mastic where panels met to ensure joints did not transmit undue sound. Ceiling frames were installed last with the air handling units and ducting installed on site.

We subsequently installed services and doors over a further six-month period. Baffles were required in ducting lengths to dampen airborne sound and John Cherrey made two custom glazed doors to acoustic specifications (Fig. 6.26). These allowed for the space to be closed and acheive the high levels of acoustic privacy desired. At this point, we had reached a state where the room could be used for teaching. The final step of installing the interior lining was completed over several further months. Once cut, we lacquered parts and then mounted these on battens which could be hung off the interior lining. Pairs of panels were matched for ease of transport and storage. These pairs of panels were then hung in place opposite one another, providing a rough symmetry of pattern but inverse form as a finish to the space.

Through this prototype we explicitly sought to invent a fabrication technique which could drive a unique design outcome. The system of panels and their form capture this and embody both opportunities and limitations of this fabrication. While the approach was consistent, the many unknowns of fabrication kept the design open until just before final production, reflecting layers of design decision through the project.

As a prototype for production, we pushed the robotic fabrication technique to a robust state in which panels could be fabricated rapidly and accurately. With a suitable bandsaw blade, the final cutting of parts ran in continuous sessions of up to 8 hours, with each program cutting a blank in approximately 8 minutes, with the part moving through the blade at a rate of 10mm per second (Fig 6.21). At this speed, we have clear geometric limits for these ruled surfaces at two widths. For 140mm wide parts, we could achieve a maximum twist across the blade of 15 degrees per 100mm travel. For parts half that width, we could twist twice as much. This is a speed and quality of production which suggest that the technique could be a cost effective approach in further situations. Further detail on the connections between design and fabrication can also be accessed through publications (Williams, N. and Cherrey, J., 2016).

Fig 6.25 Timelapse images showing installation of room shell floor and walls panels over two days.

Fig 6.26 Exterior view of the Music Room showing entry doors and wall to adjacent library.

Fig 6.27. The interior of the completed Music Room with panels arranged vertically around the space.

DESIGN TRAJEC-TORIES

The workflows developed through small architectural commissions provide discrete examples of modular systems, assembled from diverse activities. Many design ideas from these systems have been extended into further project work, with development undertaken at different levels of detail. The following section captures three trajectories of this development focused on the scales of activity, task and function.

Collaborators:

Dharman Gersch
Kristof Crolla
Richard Blythe
Paul Miniufie
Amaury Thomas
Pantea Alambeigi
Chen Can Hui
Jane Burry

7.1 The Termite Plugin: Functions for Plugging Design into 5-Axis Routing

7.1.1 Termite Background

Termite is a plugin for *Grasshopper*, offering tools to generate programs to run CNC routers and linking these to parametric models. It directly extends the set of code functions created using *Rhinoscript* libraries developed to generate cutting files for MDF frames in the FabPod project (see 4.2.4). These libraries translate specific input geometry to generic toolpaths which were subsequently processes to machine programs. *Termite* extends this functionality to broader inputs and outputs. An alpha release has been developed and we have published on the use of the plugin for research (Williams and Gersch, 2016).

The code development has been led by Dharman Gersch, a former student assistant on the FabPod. It has been developed in the Python language and uses the *RhinoCommon* platform to access functionality and datatypes within *McNeel Rhinoceros*. I have contributed high-level input to the development, to organise and structure code, and to design workflows at several scales.

7.1.2 First Functions for Workflows

We conceived *Termite* as a simple tool, targeting designers with only basic knowledge of CNC machine programming. Many CAM packages present a complex set of options, with excessive detail creating challenges for novice users. Building on the modularity in other example, our ambition is manifest as a simple chains of workflow components to translate information geometry into machine files. Five basic steps have been outlined: defining tool and material to be machined; defining geometry; defining machining operations; defining a machine; and generating a program file. A reverse flow of information, from machine file to geometry is further enabled by ‘parsing’ a file to preview a tool’s trajectory. These cover two tasks in simple workflows (Fig. 7.01).

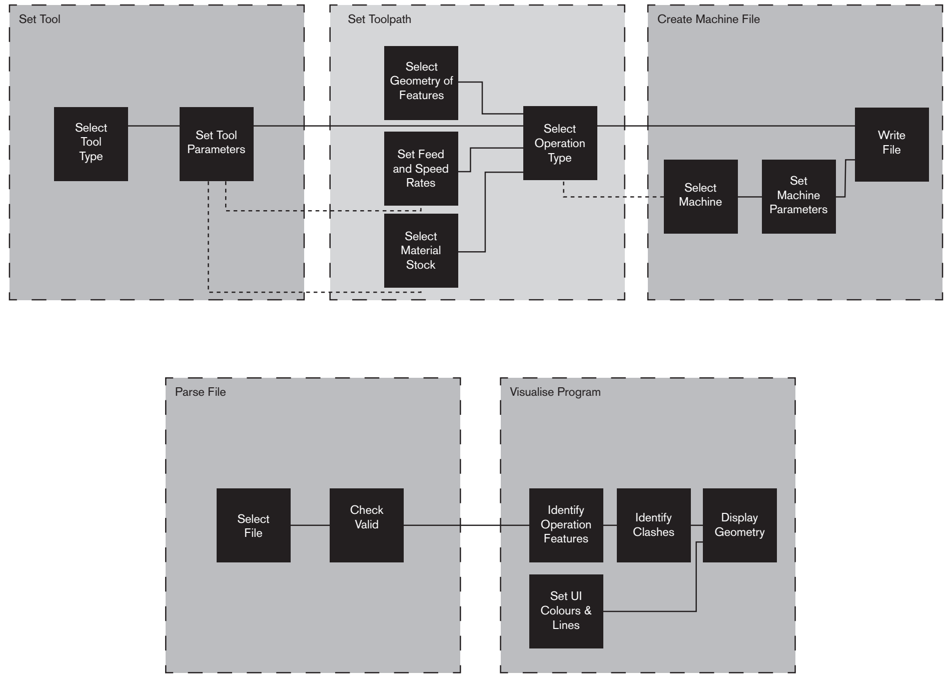


Fig. 7.01. Two basic workflows to cover Tasks of writing CNC machine programs (top) and visualising existing programs (bottom).

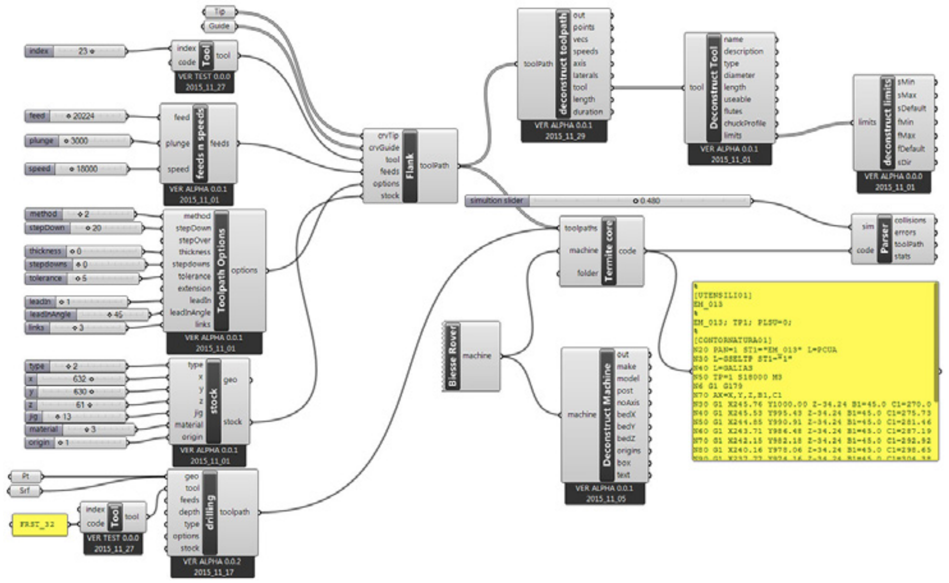


Fig. 7.02. The first release of Grasshopper components spanning all functions in typical workflows.

Between the functions outlined above are a series of custom datatypes, created to interface functions:

- Tool: A class representing the physical tools which are plugged into a router spindle. Key parameters include physical dimensions (length, diameter etc.) and preferences for operating speeds.
- Toolpath: A class representing a movement of a tool. It is composed of a series of point locations, orientation vectors and operating speeds.
- Stock: A class representing a material blank. Key parameters include either simple dimensions (length width height) or a custom shape, and information for suitable operating speeds.
- Machine: A class representing a CNC machine. It is composed of parameters and generic information required by program files for that machine.

Using these data types and working through simple steps, the first release of Termite has been developed to test workflows (Fig. 7.02). Components for key machine operations have been implemented for flank cutting (using the flank of a tool, common for routers), drilling (using the tip of a tool), cutting with a saw (Fig. 7.03), and surface milling (Fig. 7.04). Data for a library of some 20 tools has been imported and two types of machines have been implemented.

Workflows using *Termite* range in complexity. Using default values functions to set parameters such as a tool's cutting speed, are relatively quick and simple. For example, to cut out a shape from a board using a 5-axis machine, a tool and a pair of curves can be added to a 'Flank Milling' component. By connecting this further to a 'Core' component, a valid machining file can be generated. Alternatively, more detailed workflows can be created to control and refine detail of the machining. For example, if the cut result described above is of poor quality, a user can work through further functions to manually set parameters of the tool, toolpath and stock. This requires that a user implements further functions, with interdependencies highlighted through trade-offs between parameters.

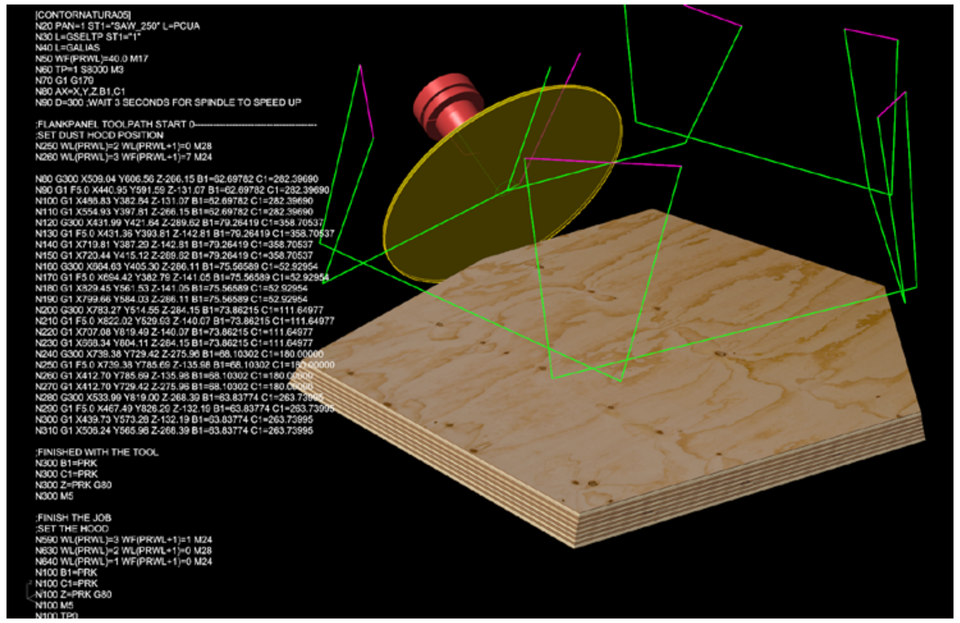


Fig. 7.03. Screenshot of Termite components for flank cutting parts with a saw from a sheet. The pink lines highlight proposed toolpaths and are flexible with the parametric model.

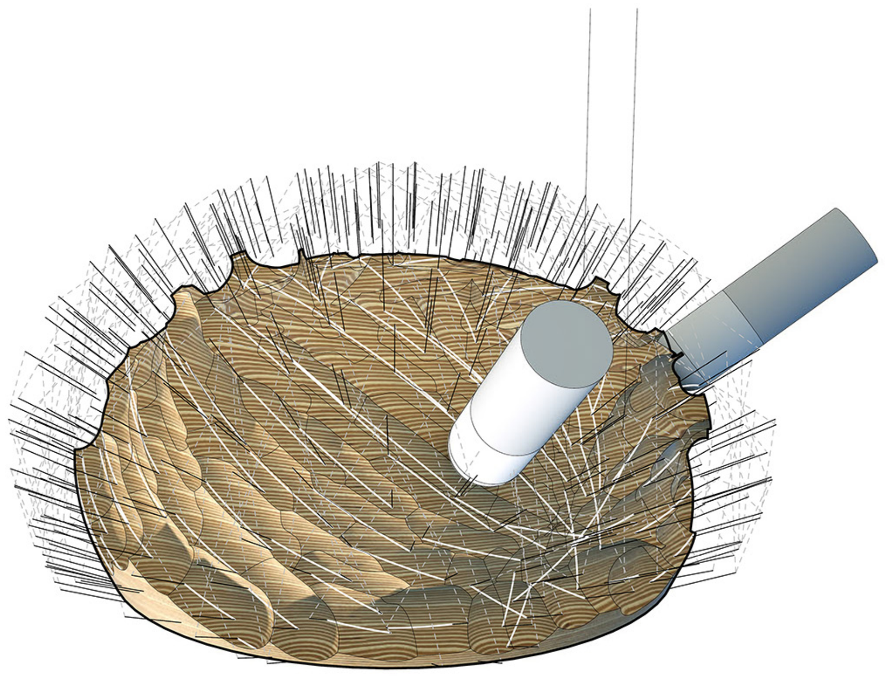


Fig. 7.04. Screenshot of a workflow using Termite components to mill a form from a block of material.. Again, pink lines highlight proposed toolpaths and provides feedback to a designer.

7.1.3 Modular Code for Generic Functions

The modularity of the code Functions here directly relates to the term as it is used in computer science. These provide a robust base layer of functionality with each component doing one thing accurately and reliably. At a broader scale of Tasks, a user is able to manipulate the order of functions and adjust key parameters. This flexibility is essential to meeting project needs, providing trade-offs between function and flexibility for users. This demands, however, a looser coupling of functions at this scale.

Through this package we can also clarify distinctions between modular workflows and object-oriented programming (en.wikipedia.org/wiki/Modular_programming). The code for *Termite* is written in an object-oriented language *Python*, and we have created custom datatypes as described above. These datatypes are important to the usabi;lity of the *Termite* tools, however, are distinct from the functionality of the workflows created with them.

7.2 Approximating Freeform Surfaces with Planar Facets: Creating Tasks to Tessellate Form

7.2.1 Introduction to Planar Facets

Over the past two decades, freeform surfaces have become intrinsically linked to non-standard architecture (Mennan, 2008, 171). Irregular and doubly-curved forms have, however, presented challenges to construction. A common approach to solving this tension is to approximate freeform shapes with a series of facets, a continuous array of planar surfaces. These planes provide references for managing geometry, and allow a designer to easily fabricate with sheet materials.

Through several pieces of research I have, with collaborators, attempted to approximate freeform surfaces with planar facets. These have had different constraints and a series of appraches are discussed here. In each case we have aspired to maximise the modularity of the workflow as a Task. Where calculations are linear this is

Fig. 7.05. Timber components being fabricated on a Biesse Rover router, programmed using *Termite*.

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Fig. 7.06. A delanay triangulation (grey) of points (red) with the circles (in blue) showing inverse arrangement of Voronoi cells.

relatively straightforward. Where goemetry requires alternative approaches, this is more difficult.

7.2.2 Linear Solutions for Simple Surfaces

In Cartesian space, the simplest facet is three-sided, a triangle. Triangulations of complex shapes have long been used in computer graphics, with common approaches including the 'Delaunay Triangulation', a solution in which the angles of triangles are at most regular, avoiding overly acute angles. This solution can be calculated linearly for any distribution of points, the modularity of which is underscored by a component in *Grasshopper*. The inverse geometry of the Delaunay triangulation cells is a set of Voronoi cells, with each edge of a cells perpendicular to the edge of a triangle (Fig. 7.06).

For two-dimensional arrangements of points, a *Grasshopper* component can be used. For freeform shapes, however, the rules for setting out Voronoi cells cannot be readily applied. There are exceptions of three-dimensional surfaces and I have already discussed the Voronio algorithm applied to spherical geometries for the FabPod (see Section 4.1.2). Here, planar facets were distributed across surfaces using a Voronoi algorithm which was further oriented to the centre point of a given sphere. An algorithm was created by Daniel Davis (Fig. 7.07) and is applicable to any sphere.

A further example comes from the Penumbra project on which I collaborated with Richard Blythe, Paul Minifie and Amaury Thomas. Here we designed freeform surfaces for a prototype panel. A series of component 'cells' was designed across these surfaces. We began by projecting these surfaces to a plane and finding a Voronoi solution for a given set of points, representing the centres of the component cells. We then created a second order of triangular facets, with each triangle defined by the centre of each cell and an edge of a Voronoi cell. When projected these back onto the freeform surfaces. Each cell component therefore had faceted faces meeting at shared edges with neighbouring cells (Fig 7.08). This chain of Functions formed a Task to reliably facet the design surfaces, within limits. A primary constraint was that a surface

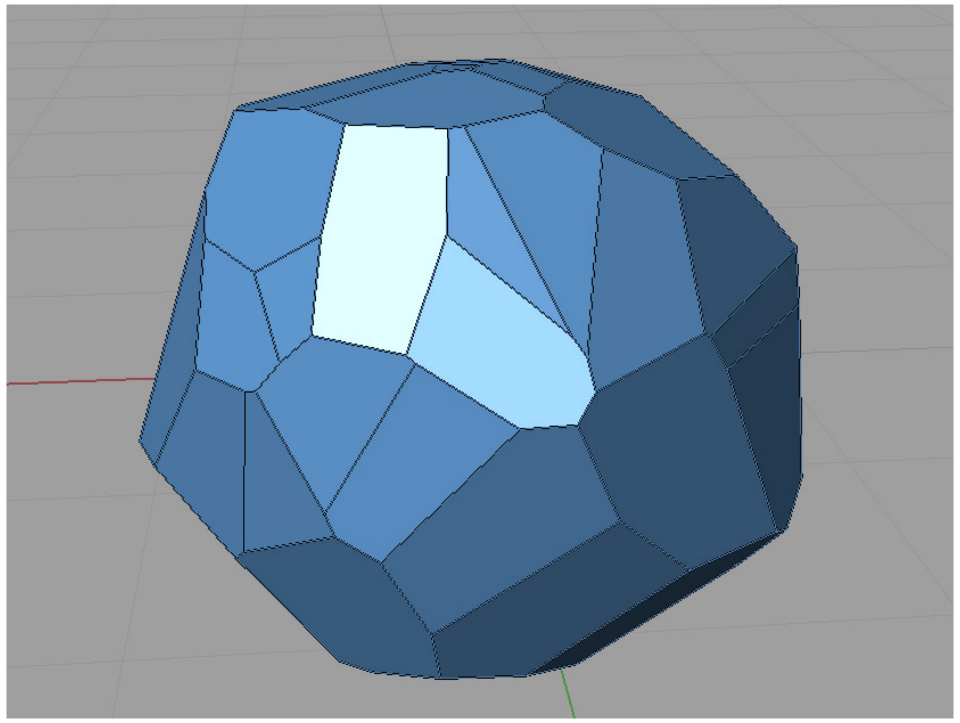

Fig. 7.07. A screenshot of a spherical voronoi tool developed by Daniel Davis for the FabPod.

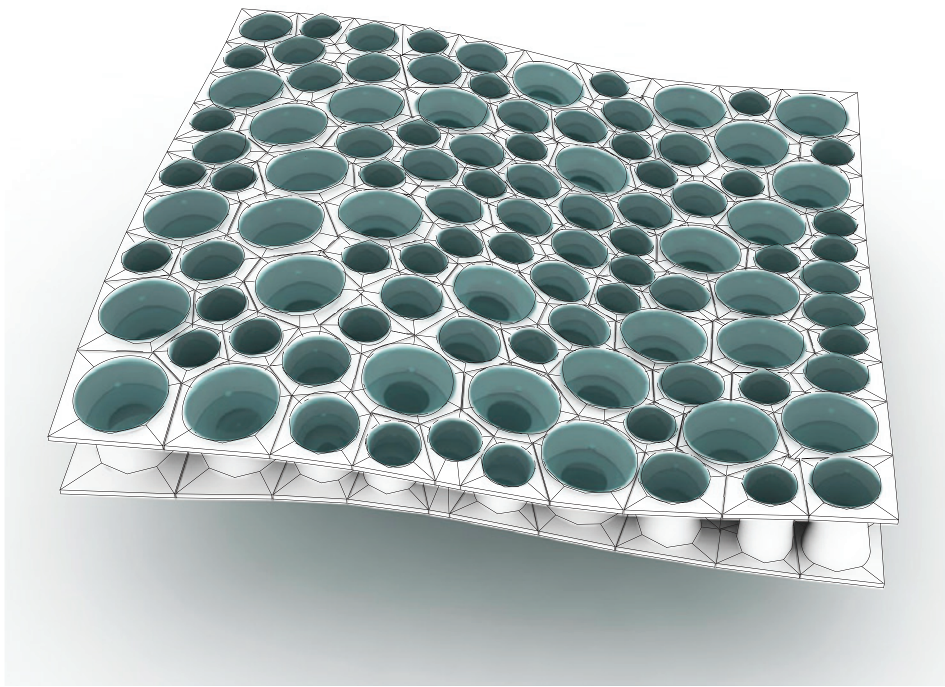

Fig. 7.08. The triangulated surfaces for the Penumbra prototype, with cell components triangulated to ensure they meet neighbours at shared, linear edges.

be projected onto a plane without overlapping. As such, this cannot be applied to surfaces which are more three dimensional.

7.2.3 Non-Linear Solutions for Unconstrained Surfaces

For unconstrained, freeform surfaces, techniques have been proposed and implemented across communities in mathematics, computer graphics and architectural geometry. Working with Kristof Crolla on the SmartNodes project (Williams et. al, 2015), we explored techniques for creating planar facets with pentagonal and hexagonal boundaries. This project proposed a shell structure, with facets conceived as divisions of a driver surface, creating a series of flat, easy to fabricate panels between structural members (Crolla et al., 2014, 311). We selected the tangent plane intersection method (Cutler and Whiting, 2007, 12) in which a series of planar facets are adjusted in location and orientation. This requires a sequence of looped Functions to adjust the orientation of planar facets until a solution is found.

Our methods proved successful when applied to areas of synclastic and anticlastic geometry with relatively good degrees of curvature. However, where a surface transitioned between the two conditions and became flat or singly curved, results were unreliable. After several months of intermittent work, we grudgingly surrendered and moved on without resolving this aspect of the problem.

Shortly after this, two alternative approaches were published within the computational design community. The first of these used an agent-based approach to locate suitable points on a surface in which to locate each facet (Schwinn et. al., 2014, Fig. 7.9). This was developed and applied to a design of the Landesgartenschau pavilion by the *Institute of Computational Design*, Stuttgart. These researchers had some success, although the technique similarly has problems where forms are singly-curved or close to flat (Schwinn et. al., 2014, 182).

The second solution has been provided by Daniel Piker, using his *Kangaroo* plugin (Fig. 7.10). Here locally hexagonal forms can each be flattened by local

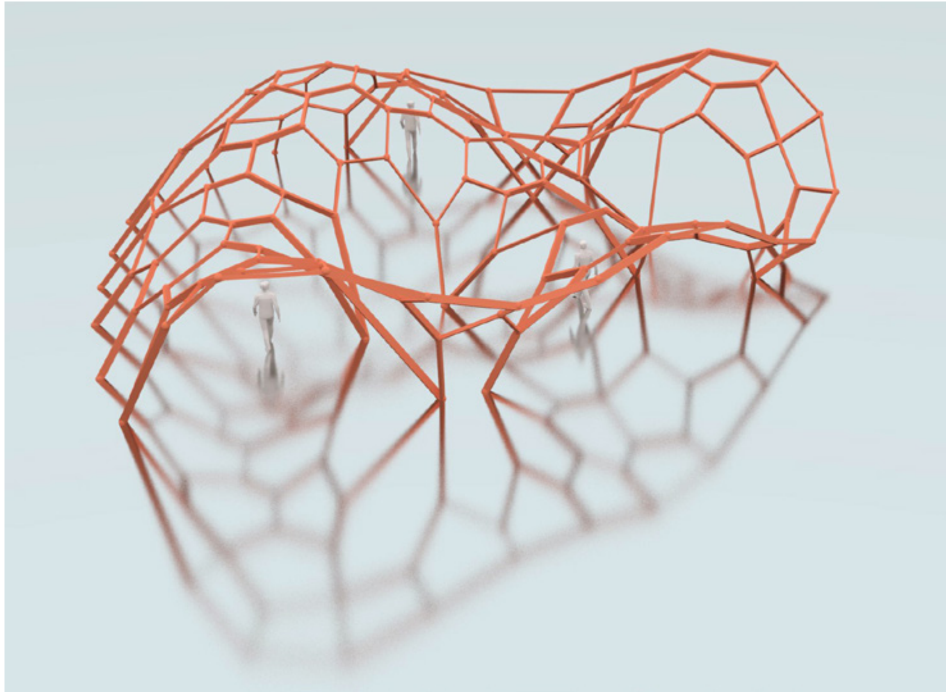

Fig. 7.09. A screenshot of the freeform surface, approximated with facets. Over two-thirds of the facets were planar, while others were left with curvature to accommodate overall form.

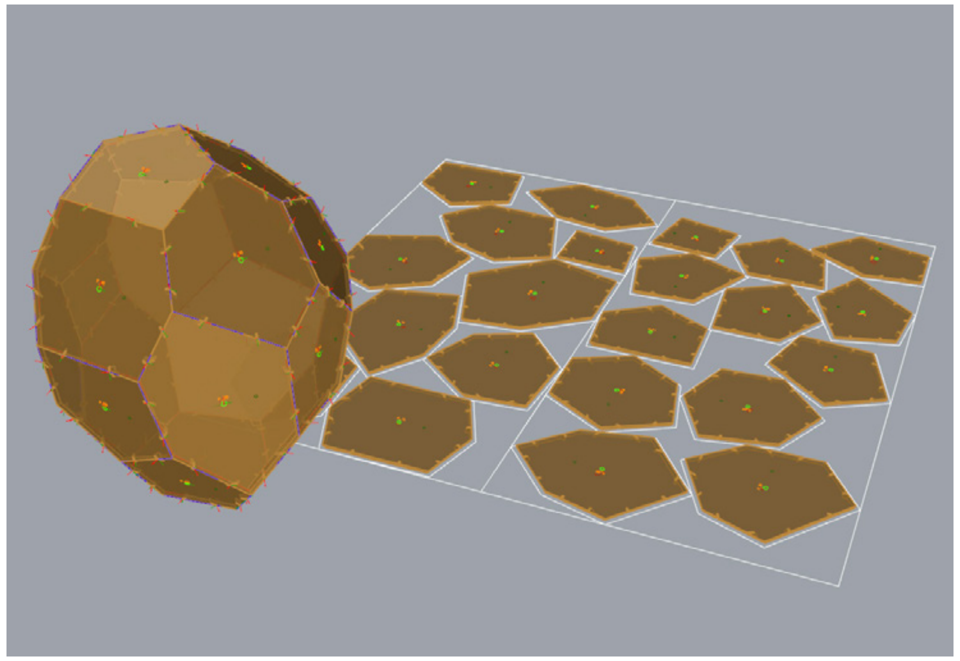

Fig. 7.10. A faceted freeform 'egg' which with planar hexagonal facets defined using Daniel Piker's Kangaroo plugin for *Rhinoceros*. Indiviual parts are laid out for cutting (right).

constraints, starting from a non-planar condition and responding to local forces while retaining links within the network of members. This physics-based approach can be implemented through plugging together *Kangaroo* components within *Grasshopper*. The non-linear task of flattening is handled by *Kangaroo's* solver component and has been developed to be a most solutions. Through teaching a workshop with Dharman Gersch, we applied this technique to a range of freeform surfaces. We then linked these facets to our *Termite* tools to fabricate prototypes (Fig. 7.11).

7.2.4 Creating Tasks of Varying Degrees of Modularity

In the workflows discussed here, algorithms to approximate freeform surfaces with planar facets are implemented as Tasks. Some of these are composed of a linear arrangement of Functions. Once these are created, they can be implemented with a high-degree of modularity, providing robust and predictable ourtcomes. Others require a non-linear algorithm (Fig. 7.12) and the added difficulty in finding solutions demands that these are of a lower degree of modularity. In these modules, key functions are separated by evaluations, often in the form of conditional statements to decide how to proceed. While this can be handled by code blocks it is more loosely coupled and the workflow more easily broken.

These brief accounts of several research projects covers situations which share the challenge of approximating a freeform shape with planar facets. This is a broad field of research including much work from others not mentioned here, notably Helmut Pottman and colleagues (Wallner et. al., 2011, 74). This recurring challenge highlights an area where reuse and sharing of algorithms has clear benefit both to the individual designer and potential to contribute back to a broader community. When facing the same challenge in a new situation, I have looked to a range of solutions, including those previously used. A further example is discussed in the second FabPod project (see section 7.3). Over the short period of this research, several new solutions have been shared among online digital design communities, commonly through online forums. This ability to package and share solutions, whether as Grasshopper components or elsewhere, is a primary feature of modularity.

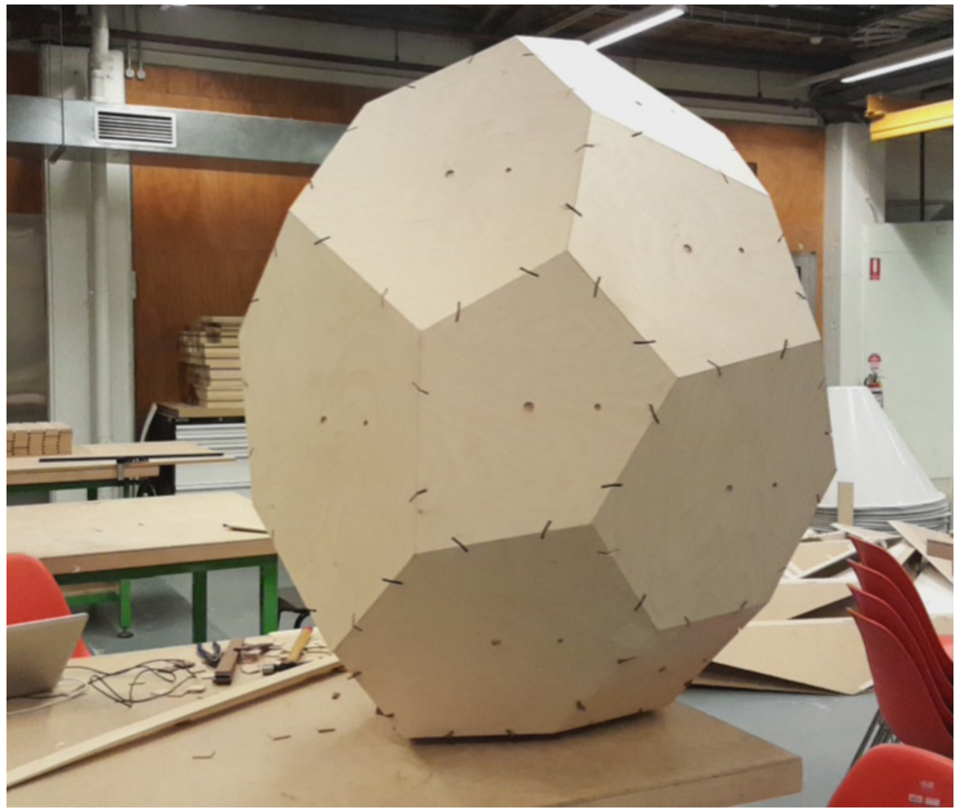

Fig. 7.11. The faceted egg form fabricated as a series of 5-axis cut plywood panels.

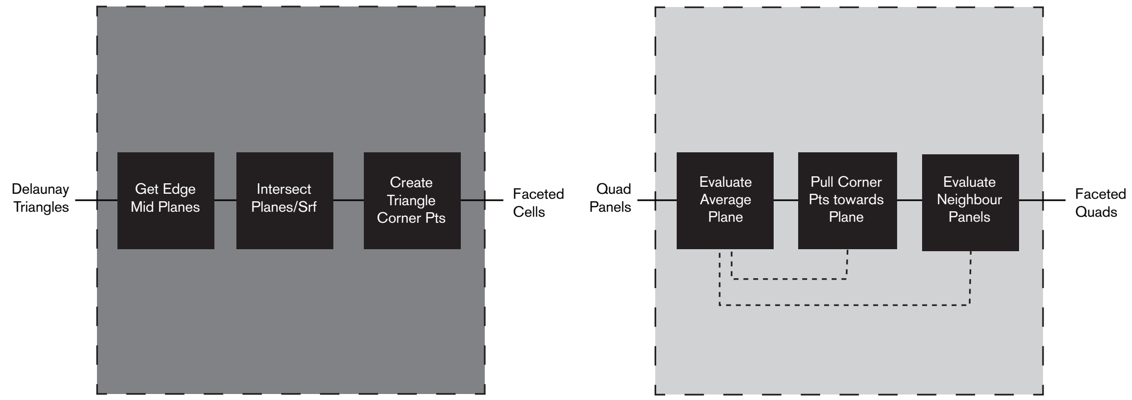

Fig. 7.12. Two examples of Tasks to facet freeform surfaces. With linear functionality (left), modularity can be to a higher degree than where non-linear (right).

7.3 FabPod 2 : Re-purposing Activities to Transform a Design System

7.3.1 FabPod 2 Introduction

Following the successful completion of the first FabPod project, funding for further prototype meeting room enclosures was attained. Many of the team from the original project were not available and new research collaborators were added to the team. After acoustic testing of the original FabPod (Fig. 7.13), I led the development of the Design System with the ambition for this next iteration not to refine or repeat what was done previously but to propose a new design, only loosely related to the original.

Some basic principles remained, such as the design of component 'cells' for prefabrication and onsite installation (Fig. 7.14). We further worked across the three Divisions of the original, addressing form, acoustic performance and fabrication. However, through identifying limitations we replaced a series of Activities from the original system and designed new ones as needed. Through a series of mockups and tests, I established these new Activities and their role within the Design System. I then stepped aside to leave the final design prototyping to a team led by Chen Can Hui. I have made occasional input to clarify aspects of the workflow.

7.3.2 Modifying Activities for Designing Form

In the original FabPod, the relationship between component form (hyperboloid) and overall form (intersected spheres) provided a clear solution space for formal design exploration. While this constraint proved productive to creating a space of design solutions and extending existing research, here we proposed to revisit and remove this constraint.

The first scale addressed was of the component hyperboloid. Informal feedback from acoustic experts indicated that alternative forms could be used to create a similarly articulated wall surface with varied depth and material. Further, I sought to

Fig. 7.13. Researchers Sipei Zhang and Pantea Alambeigi measure sound levels in the FabPod.

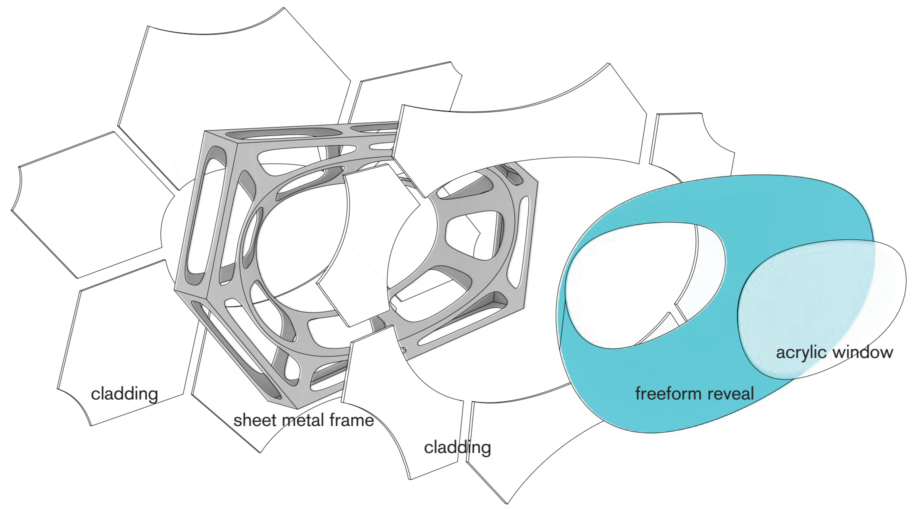

Fig. 7.14. An exploded view of components for the FabPod 2. A metal frame has a freeform oculus at its centre. The frame is clad with parts which span joints to neighbouring cells.

move beyond trimming of a repeated form to create a set of unique but related forms. I turned my attention to developable geometry, those which can be created from one surface to another without stretching or compressing. While it is relatively common to develop flat sheets into other forms, however, other developable forms can equally be reshaped. I looked into cones as a suitable starting point and identified that conical shape could be developed into a series of unique, tapered extrusions. These forms can be described through a planar profile curve and fixed taper angle. From this information, a second profile curve can be mapped in an offset plane to that of the first curve, giving the form of a unique component (Fig. 7.15).

To identify how this can be developed from a cone required mapping the two profile curves to the cone form. I created some parametric models and achieved approximate solutions to a tolerance on 1mm. Collaborator Daniel Prohasky was then engaged on the problem. He developed an algorithm which iteratively refines a result, producing a form to within a defined tolerance. In real-time, this algorithm can calculate a result to within a tolerance of a few microns. This was developed as a *Grasshopper* component which could be plugged in for robust use by the design team.

Unconstrained by the relationship of hyperboloid to sphere, the overall form of the new FabPod moved away from the spherical forms of the original. Part of this shift was toward the relative simplicity of planar surfaces. These can offer efficiency where the Pod meets existing building structure, and allow for standard elements such as doors to be incorporated into the design. Alongside this, freeform surfaces were proposed and tested for acoustic performance. For detailed design, these forms were approximated through continuous arrangement of planar faces. This approximation required us to evaluate synclastic and anticlastic geometry, with solutions discussed in 7.2.3. At the point of handing the project leadership to Chen Can Hui, a number of options were in play.

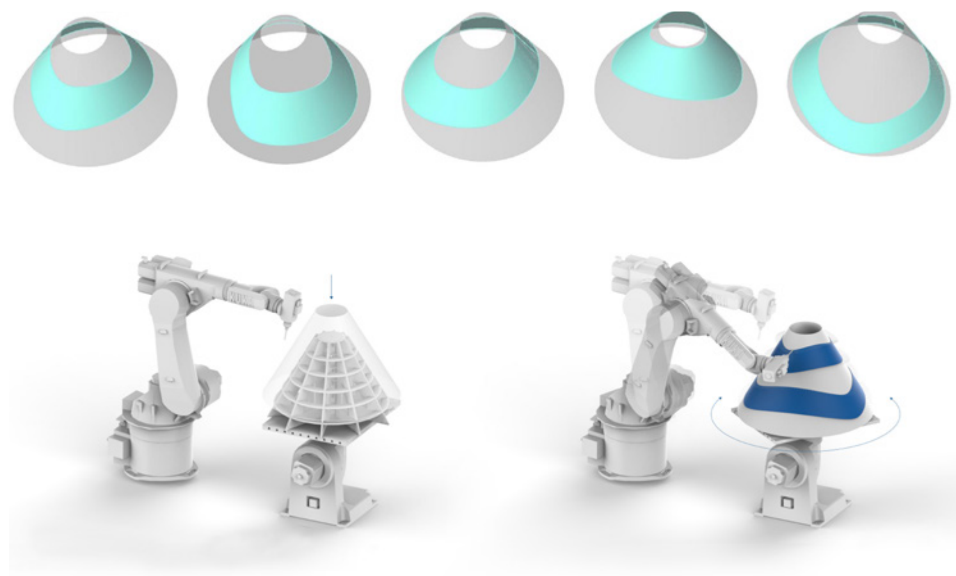

Fig 7.15. Cone forms with custom shapes within them (top). These can be cut out using a robot and roboting table (bottom). (Images: Chen Can Hui)

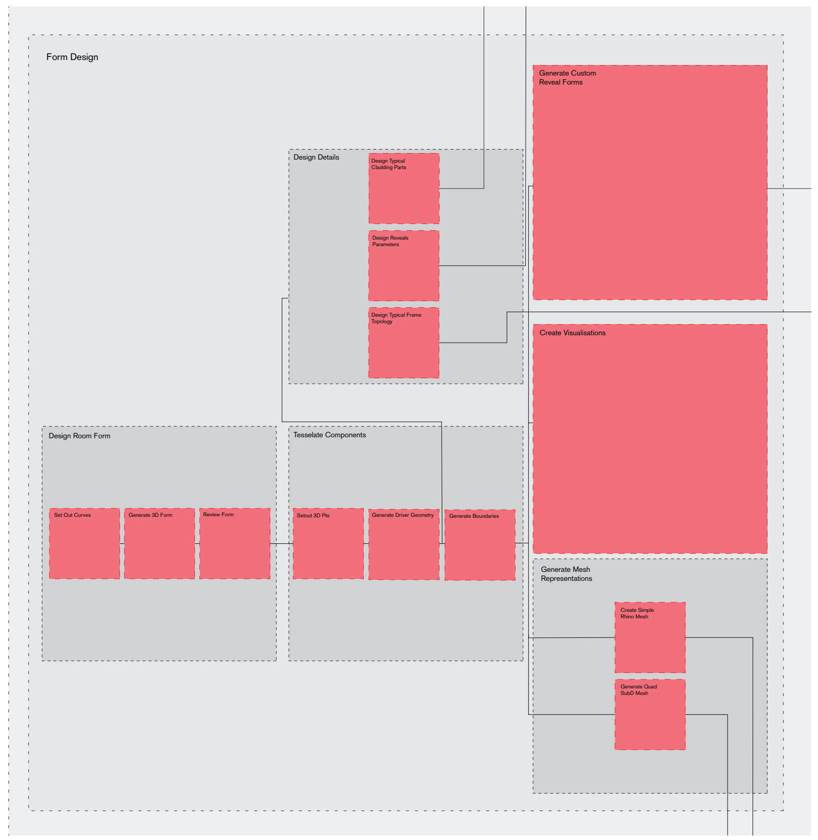

Fig 7.16. Studies for the form of the FabPod2 by myself (bottom) and Chen Can Hui (top).

7.3.3 Replacing Activities for Acoustic Analysis

The first FabPod prototype provided a productive site for acoustic testing (Alambeigi et.al., 2016, 632). Feedback on the acoustics covered two primary issues – the internal acoustic quality and the level of acoustic privacy to surrounding spaces. As mentioned above, acoustic performance of the specific hyperboloid forms in scattering sound was not easily measured. Furthermore, the acoustic diffusivity of the space could not be readily tested in place. The significance of the hypothesis around sound diffusion was also challenged by some colleagues and further research in this area put aside.

The attention of acoustics experts interested in the project shifted to issues of privacy, primarily the transmission of sound between interior and exterior of the enclosure. Pantea Alambeigi provided leadership in acoustic analysis and she implemented a series of new Activities. These include the simulations of speech privacy measure Sound Transmission Index (STI), at multiple locations both within and outside the proposed form. These simulations required multiple iterations in simulation package *Odeon*. I did not have direct involvement with this acoustic work, however, as with the first FabPod, mesh approximations of the design form were needed. I was involved in providing some of these through techniques for approximating design surfaces using quadrilateral mesh faces at several scales of detail.

7.3.4 Modifying Activities for Fabrication

Where I continued to have a peripheral role in acoustics, my role focused on designing Activities for fabrications, suited to the new geometry of component cells. Incorporating the conical forms as reveals in each cell, a configuration of parts for each cell component was designed (Fig. 7.14). As with the original FabPod, this consists of a frame with a formed reveal and cladding attached to each side. Each of these elements have in turn been redesigned and these changes are manifest in re-purposed Activities.

In a similar vein to the FabPod, the fabrication of conical forms required two activities: manufacturing material blanks of a common base form; and subsequently

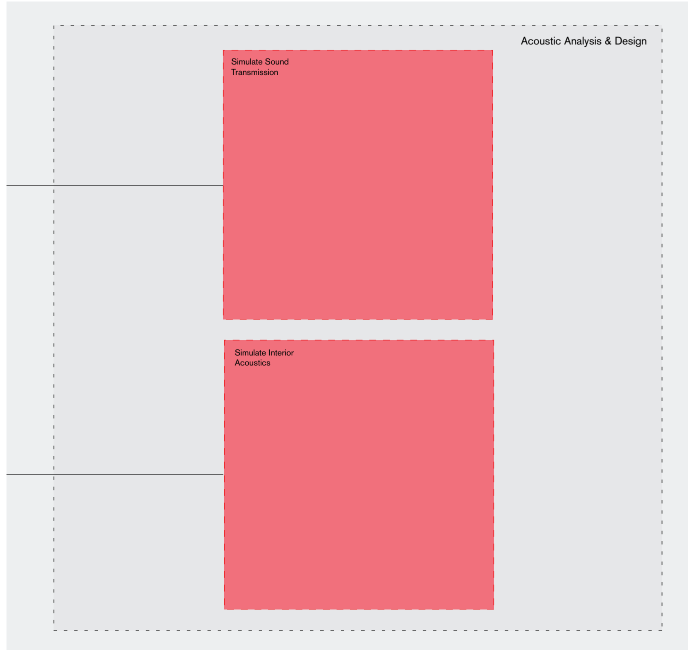

Fig 7.17. Acoustic simulations of design proposals for FabPod2 in *Odeon* (images: Pantea Alambeigi)

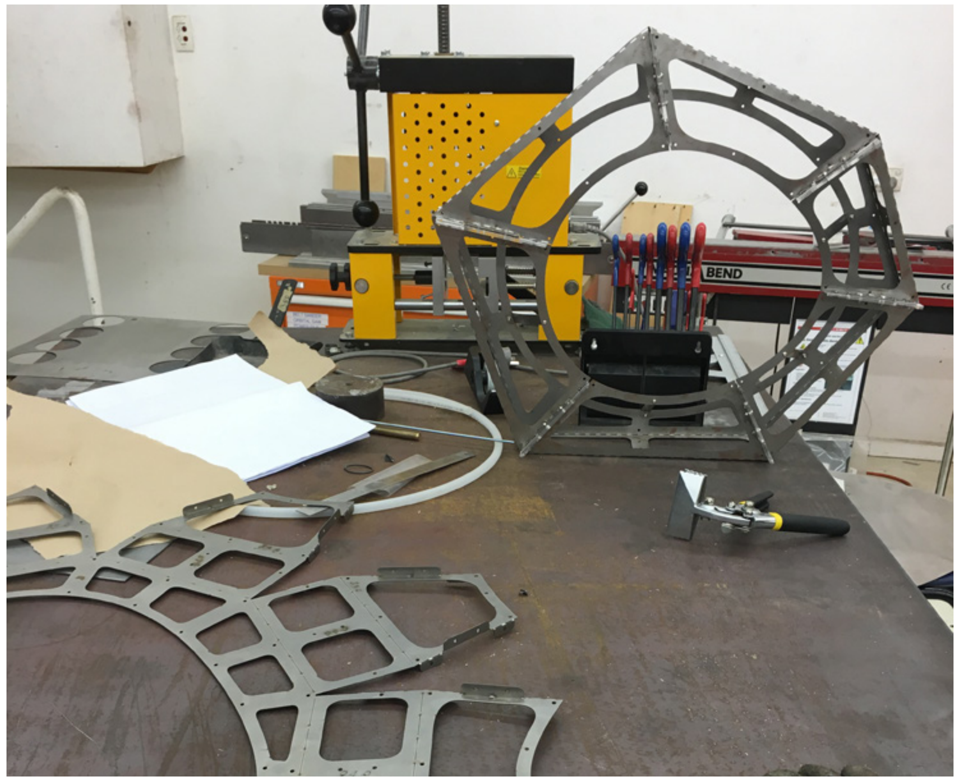

Fig 7.18. Frames are lasercut from sheetmetal and folded into specific shapes, with overlapped holes locking in correct locations and arrangements.

trimming these to a specific shape. Within these activities, however, are different types and arrangements of tasks. The blank parts have been fabricated through thermoformed plastic, with the mould made by the contractor. Trimming parts, requires blanks to be mounted to a further jig, in parallel to programming both the robot and rotating table. Using an end milling tool on the robot, blanks are then cut to unique shapes (Fig. 7.19). As with much of the research here, this activity has been through an extended period to refine it in terms of speed and accuracy. It is planned that a further task of painting the parts will finish these parts.

The activity of cutting frames shifts in technique from routing mdf parts with a 5-axis machine lasercutting metal. While the first technique provides significant flexibility in the shape of parts, the subsequent activity of assembling cells faced challenges in controlling quality for the original FabPod. This required numerous jigs and checks to ensure frames were assembled within acceptable tolerances. As an alternative, I proposed a system of sheet metal frames, laser cut from sheet material. These lasercut parts are designed to be folded around perforated lines, overlapping back on themselves with fixings (rivets or bolts) placed through overlapping holes to lock in place a specific form (Fig. 7.18). As with the fabrication of custom reveals, the fabrication of frames follows the same sequence of Activities in each FabPod. This begins with creating a detailed model, moving to the fabrication of parts which are then assembled. The Tasks within the fabrication sequence are replaced (Fig 7.20).

Similar repurposing of Activities continues through the fabrication Division of the project. Fabricated parts converge into a linear chain of assembly Activities, with offsite prefabrication once again demanded. While some aspects of the project are still being finalised, this sequence of Activities will remain consistent, with any changes made at finer levels of detail.

7.3.5 A Re-purposed Design System

As these examples show, the Design System for the second FabPod maintains explicit ties to that of the original project, despite some significant changes across many

Fig 7.19. Cutting a plastic part from a cone with a robot.

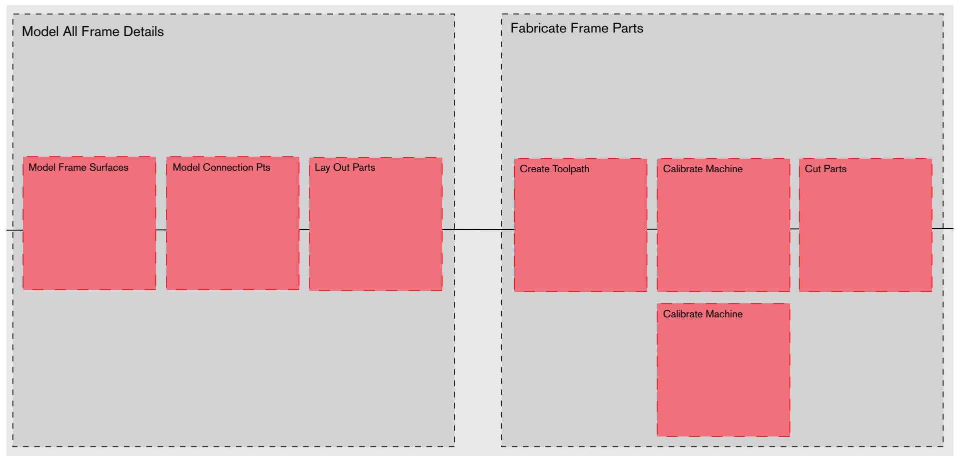

Fig 7.20. Modified and replaced Activities and Tasks for fabricating frames.

of the tools and techiques of design (Fig. 7.23). This continuity is both desired and necessary, with an arrangement of process created at a broad scale of workflow, and then refined through multiple prototypes. A key example of this continuity lies in the part-whole relationship of components and overall form of the enclosure and is manifest in the workflow chain running through formal design and fabrication. Activities here follow the sequence of the original and changes occur at a finer level of detail through Tasks and Functions.

This repurposing of a Design System also highlights differences in degree of modularity at which I access knowledge and design process. In both FabPod projects, I have had little engagement with acoustic analysis beyond the scale of Activity. In moving from the first to second projects, Activities are replaced, and follow a shift in individual leadership and research focus within this Division. In contrast, I have driven the design of form and fabrication process from the bottom up. Activities with these have been edited through replacing Tasks and Functions.

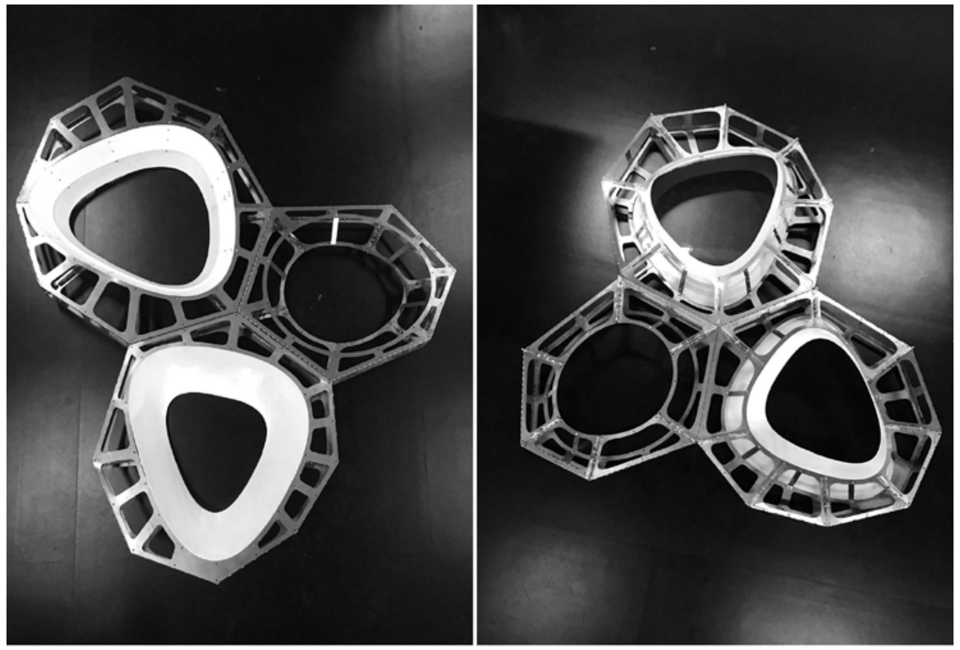

Fig7.21. A prototype of metal frames and reveals, assembled for testing. (images: Chen Can Hui).

Fig. 7.22. Full scale test made to test techniques for fabrication of the FabPod2 prototype.

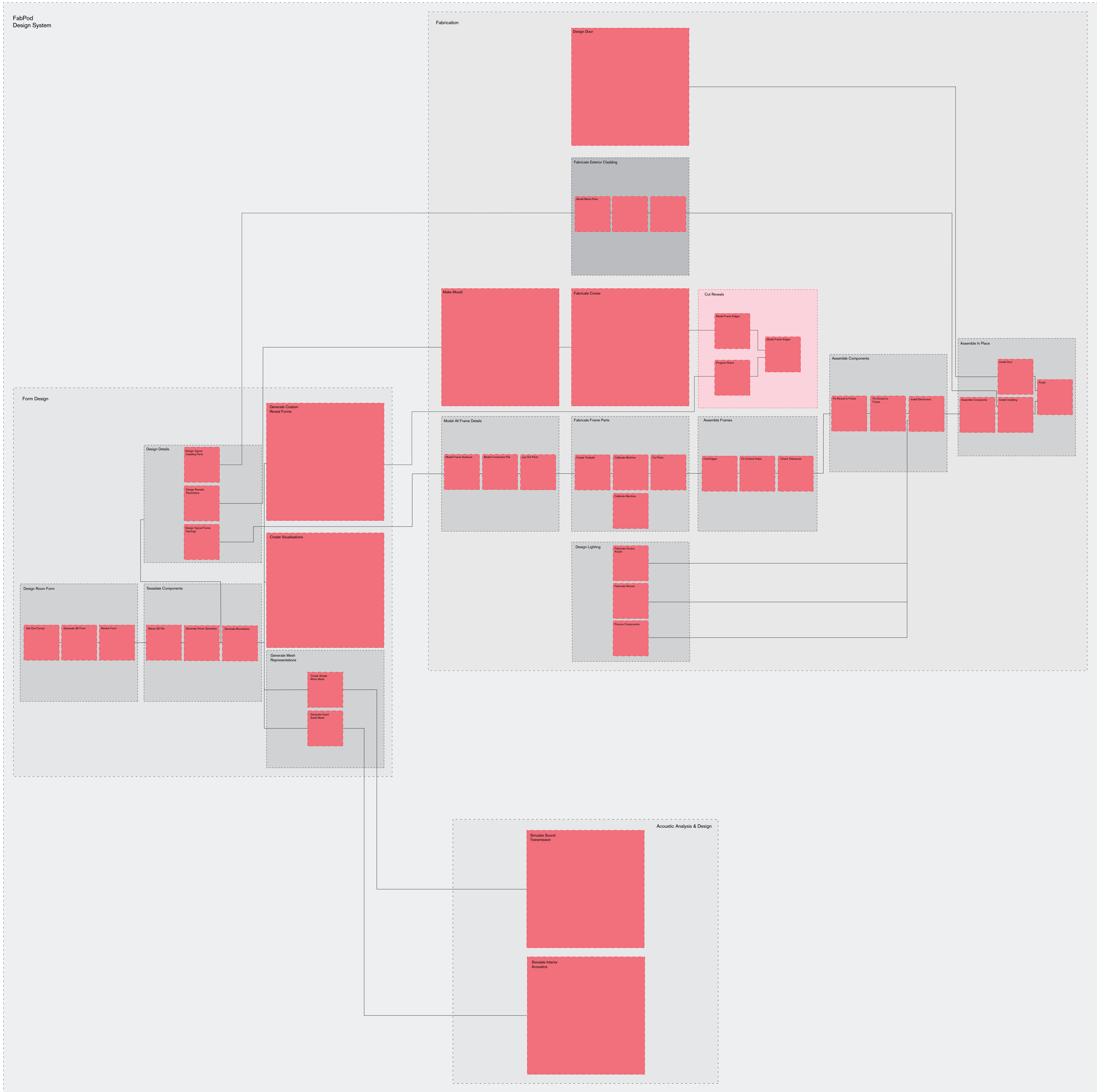

Fig 7.23. Replaced and modified Activities (in red) of the Design System from the original FabPod.

8. Discussion

This research set out to interrogate the changing practice of architecture in the context of a broadened domain spanning the design form and material, digital and conventional fabrication techniques, and the simulation of specific aspects of performance. This focus on practice fits alongside other research into digital technologies which highlights specific tools, techniques and design representations. I do not wish to diminish or gloss over the importance of such outcomes within this research or others. Indeed, the individual projects herein have been regularly exhibited and presented through peer-reviewed conference papers and journal articles (see10.3).

Through this interrogation of practice, I am not aiming to scale individual results into generalised formulas for design. Such generalisations would inevitably be incomplete and obsolete, and add constraints to design which would be resisted by designers who value difficulty (Willis and Woodward, 2010, 201). To better understand design practice, I have addressed the modularity of process at multiple scales and applied to varying degrees. This operates across processes which use digital computers and those which are manual. It also spans the technically precise and constrained demands of digital tools, and ambiguity which is embedded in design.

Building on the project material in the previous chapter, I here review the various scales of process and discuss the degree of modularity in each. This demonstrates a modularity of process and articulates typical roles which have emerged across this research. As well, these scales and degrees help to frame key priorities for design. I will discuss here ways that through modularity we create standards to manage complexity and differentiation, we undertake work in parallel to enhance design collaboration, and we navigate unknown outcome to enrich exploration. Through explicitly recognising modularity in our design process, we can consider some key issues for a practice in which we plug together a diverse set of tools and techniques for design.

8.1 Levels of Detail, Degrees of Modularity

Through the project chapters, I discussed key modules at varying levels of detail from a base level of Functions to broad Design Systems created to produce full-scale architectural prototypes. In this section I provide an overview of the type and degree of modularity at each level, illustrated with examples from the project material of key roles emerging through this modularity of practice (table 8.1). This addresses a primary aim of this research, to demonstrate a modularity of process.

Beyond simply demonstrating modularity, I wish to articulate the character of this modularity. There is clear pattern across the project material of high degrees of modularity at finer levels of detail, diminishing of this degree as we look more broadly. While Elemental Functions are always highly modular, Design Systems are always fuzzy. Between these scales are varying degrees of modularity, with internal coupling and robustness dependent on specific flows of information in design process.

Level of Detail	Degree of Modularity	Emerging Roles
Elemental Function	High	Easily understood and integrated into systems, limited functionality.
Basic Task	Medium - High	Easily learnt, high potential for automation.
Activity	Medium – High	Requiring skill, potential for outsourcing.
Division	Medium - Low	Requiring specific leadership, Potential for services.
Design System	Low - None	Potential for products.

Table 8.1. Overview of scales in workflow showing and with emerging roles for practice.

It is important to re-emphasise that the modularity described here has a level of subjectivity. The finest level of detail which is addressed also varies from case to case in the project material. In a few extreme cases, Activities are discrete modules from which greater detail cannot be distinguished. More commonly, however, we have addressed the finer detail of Basic Tasks and Elemental Functions. This reflects the

level of detail to which we had to explore in the course of design. For example, when we purchased components, we did not understand Elemental Functions which were undertaken in manufacture. Similarly, the details of calculations for acoustic simulations were not always available to us. Naturally, knowledge of this level of detail is available to someone, be it a supplier or software developer. Interrogating process to this level of detail was deemed unnecessary in undertaking the research and indeed would have unnecessarily burdened the teams. As such, I frame the modularity of process as it pertains to design, inevitably with a level of subjectivity.

8.1.1 Elemental Functions

As I have already described, Functions are a base level of detail beyond which we do not need to address in contemporary design practice. In digital design environments such as Grasshopper and in scripting libraries such as *Rhinoscript*, a base level of detail is presented and apparent. These are code functions, each with clearly defined input, function and output. Further to this are methods and functions in Software Development Platforms for *Rhinoceros* and other software from *Mathworld Matlab* to *CATIA* to *Odeon*, which are accessed variously to connect workflow and where scripting interfaces are not available. It is possible to drill down to more fundamental levels of code. The benefits of doing so, however, centre not on increased functionality but on improved speed in functions. With the processing speed of contemporary computers, and the relatively low volumes needed for the prototypes here, the speed of executing code is negligible.

For the fabrication and assembly of customised components we must control individual motions. Jigs were designed to control manual cutting, CNC operations are captured in discrete blocks of code and ordered in an efficient and effective order. As outlined by John Everett (1991, 74), where such individual motions have been central concerns to manufacturing, they have not traditionally been of much interest in construction, where an array of established tasks are used for relatively small volumes of production. However, to control the quality of fabrication within acceptable limits, processes need to be conceived for varying shapes of part as input and varied shapes produced as outputs, requiring a higher level of detail. Again, we can consider finer levels of detail, and in the highly repetitive field manufacturing these are important to efficiency. In contrast, in the context of these prototypes with low volumes, they are negligible.

8.1.2 Basic Tasks

Elemental Functions are only of limited use in design. In the project material presented here, we have used literally hundreds of such Functions, organised in various arrangements to meet specific ends. In the context of parametric schema, Davis et al (2012) have identified that in design, simple organisation of functions into groups at this scale improves the legibility of scripts, with implications in the speed of modifying and sharing these among multiple users. In the projects presented here, we often needed to share scripts and we attempted to implement good practices in grouped functions. For example, in the FabPod the Tasks of connecting spheres and tessellating with Voronoi patterns across these were instantiated as compound Grasshopper components which students couldn't accidentally break.

In the material domain, the level of expertise of individuals was also a key consideration in designing Tasks. Specific Tasks could be handled by experienced collaborator John Cherrey, however the size of our architectural prototypes demanded support, often relatively unskilled labour. In these cases, such as drilling holes in laths for the Sound Bites Shell (see 4.2.2), we needed to implement training and checking to complement the tools and jigs. In other cases, we could use CNC machines and robots for fabrication and routing parts from a sheet, for example, involved creating a program of a linear sequence of Functions. These Tasks involving digital fabrication address the transfer of information to material.

Everett identifies Tasks as the most suitable level of detail for automation in construction (1991, 102). It is easy to imagine a Task such as drilling holes being done by a machine. We can similarly automate tasks such as running acoustic simulations,

coding routines to execute batch across multiple conditions. Indeed, with time and incentive we could have automated many Tasks across the various workflows here. Such automation requires time to engineer quality and speed, often beyond the needs of the prototypes here.

Some Tasks, however, are not easily automated. I have already described that in approximating freeform surfaces with planar facets (see Section 7.2.4), linear arrangements of Functions create more modular Tasks than those which branch or are parallel. This is apparent across many of the Tasks discussed here and reflects the circular, branched or parallel workflows for design (Kilian, 2007). Where non-linear arrangements occur, automation is more difficult as complex decisions must be embedded in algorithms. Beyond the bounds of this research, there is much recent interest in fields such as machine learning which might conceivably be applied at this scale to provide highly modular solutions for designers.

8.1.3 Activities

In construction, the level of Activities is the basis for much process and for commercial relationships. Codes and manuals exist for installation and assembly of standard products and systems, with fabrication typically outsourced to a supplier. For more bespoke fabrication, the relationships with external suppliers need to be well controlled, requiring unambiguous descriptions of custom parts (Scheurer, 2013). In the project material I have presented here, good examples are the fabrication of hyperboloid components for the FabPod. To each fabricator, for pinning metal and thermoforming plastics, a hyperboloid form was communicated to a fabricator, through clear but minimal sets of information. These Activities have a high degree of modularity, largely autonomous from the design team.

In contrast, many Activities related to fabrication here were not readily available from commercial suppliers, for instance in utilising an industrial robot to cut custom parts. Demonstrating effective ways to acheive novelty is a central ambition of this research and as such we undertook Activities in-house and used significant design and testing. A prime example is the cutting of timber blanks for the Music Room (see Section 6.3.2). This Activity was developed over almost three years to achieve a situation where production could run continuously and smoothly. Further examples include the assembly of edge beams for the Sound Bites Shells, involving the design of many jigs and strategies for gluing together parts. In these cases, it was necessary to make finer levels highly modular in order to consistently execute an activity.

In the space of acoustics, a similar contrast is apparent between different conventional and unconventional analysis. Common measures such as reverberation time can be undertaken with off-the-shelf software, rendering such an activity highly modular. Less conventional measures such as calculating acoustic diffusion, a feature of the FabPod (see 4.1.2), required that we work at finer levels of detail.

8.1.4 Divisions

Divisions are the level of detail at which key expertise is typically engaged. In practice, consultants are conventionally engaged for key disciplinary knowledge and compliance. Construction is divided into key trades among contractors and in various types of organisation (Everett, 1991, 63).

In the project material here, each of the large prototypes include three Divisions for the design of form and material, the analysis of performance (acoustic or structural), and the fabrication of prototypes. For both the Music Room and Sound Bites prototypes, a fourth Division was created alongside these. Wherever possible, these Divisions engaged the skills and experience of individuals to provide leadership. In contrast to a commmercial context, this research blurs the boundaries of these Divisions to explore interdependencies between them. I worked across all Divisions, providing expertise where needed within each and in providing leadership to connect them.

For the three major prototypes, we created variations on the three Divisions to enable the research. Key features are illustrated in each:

- For the FabPod, responsibility was assigned to individuals to build aspects of the system related to form, acoustics and fabrication. Interfaces between these became a key design activity of the research with information flowing between each of the three modules in agreed formats.

- In the Sound Bites project, a fourth Division emerged to enable collaboration on the detailed design of the gridshell. This Division became central to the workflow, connected to each other division for form, structural analysis and fabrication.

- In the Music Room, a Division was developed to invent and develop the fabrication process combining robot and bandsaw. This sat alongside other Divisions for the detailed development of a fabrication technique.

A degree of modularity is necessary to enable parallel work in various Divisions. Indeed, this parallel work is essential to exploring interdependencies through design. As with complex models elsewhere (Winsberg, 2010, 262), fuzziness of modularity is important to calibrating these in relation to each other.

8.1.5 Design Systems

At the completion of each prototype, we were inevitably asked questions around how long each took to make, how much each costs, and whether we would consider transitioning to larger volume production. These questions sometimes caught exhausted design teams off-guard.

The aims of these prototypes are far from those of volume products. This echoes the contrast in practices of prototyping which I discussed in 2.2. In the research, modularity at the scale of the Design System was fleeting. Processes were arranged and related for a brief period and drawing on teams of collaborators. Furthermore they were open to be extended as conditions demanded. In this frame, modularity was largely dependent on my role connecting parts and instantiating interfaces.

Nonetheless, it is conceivable for each Design System to lead to a type of product. Each addresses a particular need and could conceivable find a broader market. This is particularly true for both the FabPod and Music Room which developed out of commissions for day-to-day spaces and respond to documented needs. This would naturally demand clarify on the types and degrees of customisation. The demands of reliable and quick production at volume would demand a significantly higher degree of modularity at the broad scale of the Design Systems.

8.2 Pros and Cons of a Modularity of Process

Addressing the design of engineering systems, Carliss Baldwin and Kim Clarke identify three purposes of modularity: “to make complexity manageable; to enable parallel work; and to accommodate future uncertainty” (2004, 1). In the projects of this research, the relevance of these purposes of modular thinking to architectural design and prototyping processes is examined in detail and through example. In this section, I explicitly relate these purposes to key design ambitions: for differentiation at multiple scales; for the exploration of interdependent aspects of form, material, fabrication and performance; and for cross-disciplinary collaboration for design. Through addressing these purposes and ambitions, here I articulate some of the benefits and challenges of modularity of process and relate them to examples from the research here.

8.2.1 Managing Complexity for Differentiation

Standardisation has become an anathema to many architects, especially among those practicing and commentating on digital design. As exemplified in forums like the *Architectures Non-standard* exhibition, digital technologies can enable organic design outcomes through seemingly organic design process, driven by intuition which “ensures a never-completed space of creativity and non-identical reproduction” (Mennan, 2008, 11). With more recent use of digital fabrication, architects have sought to “overcome the repetitive build-up of standard building elements in favour of a differentiated assembly of bespoke elements” (Gramazio Kohler, 2014, 18). At both scales, these architects are explicitly resisting specific constraints.

As a counter this, I have already noted Greg Lynn’s use of the term *family* to describe the collections of unique but related components “defined both individually and collectively at the same instance” (2008, 175). Lynn further cites the biologist Gregory Bateson to address the process of differentiation from a generic primitive to a specific part in nature. These structured relationships are underpinned by standards. Following this vein, in each of the workflows here component families are differentiated from a standard starting point. For example, in the FabPod, a hyperboloid primitive is assigned

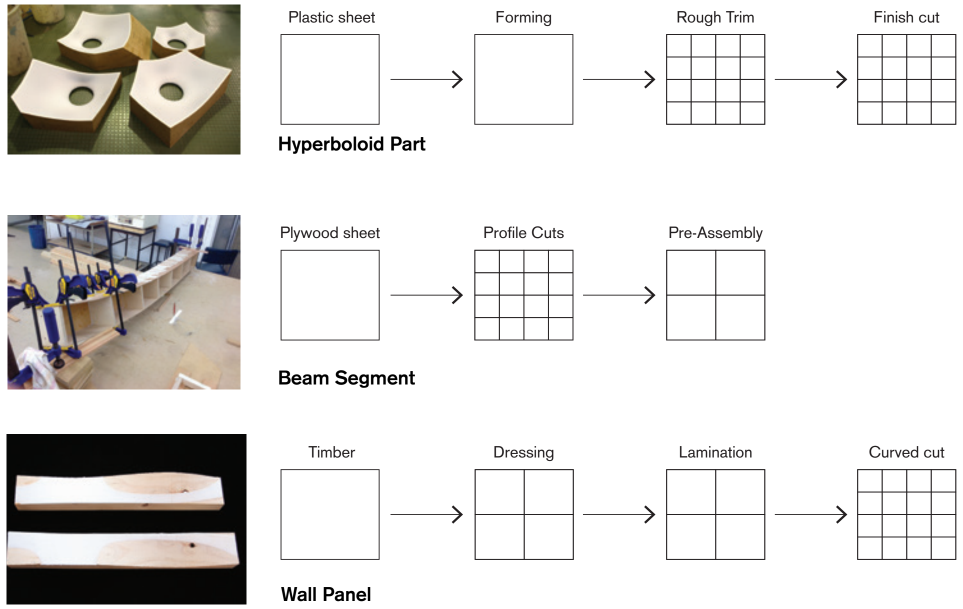

Fig 8.01. Steps in differentiating families of components, showing different orders in the numbers of differentiated parts.

a material and trimmed by a series of planes as an external border. In the Sound Bites project, curves defining axes of the timber laths are generated and differentiated through locating intersections with other axes. The ruled surfaces for faces of the robot-cut panels for the Music Room are created from control curves between panels, defined through a modular process.

In fabrication, the differentiation of material components is similarly organised around discrete process steps. Standard blanks are procured as off-the-shelf material parts. These are then differentiated through processes at the scale of Functions and Task. At each step, specifics of form and finish are imbued through constrained and repetitive process (Fig. 8.01). A similar sequence of standards steps is apparent in transforming digital representations into material parts. These are underpinned by interfaces of structured information between modules, describing specific planes, dimensions and features for fabrication. When using CNC machines, such information is used to generate and execute machine programs. A similar translation of information occurs in manual processes where tools and jigs are used to define form and control the finishing of parts.

The formal differentiation enabled by these systems extends beyond components to the scale of a piece of architecture. With flexibility in components, at this scale we are engaging with continuous and differentiated forms enabled by NURBS geometry. Varying relationships of part-to-whole are explore. For example, in both the FabPod and Music Room projects, individual components are legible, the overall form read as an aggregation of parts. In the Sound Bites shell, the continuous perimeter beams are broken into components at arbitrary points, with each segment not read in comparison to the whole. In each of these outcomes, differentiation is enabled through a careful of standards in a modular process.

Embedded in these modular process steps standardised interfaces defining flows of information. Where design demands high degrees of differentiation, these are particularly critical to managing an increased amount and complexity of information. When defining a family of component parts, we are specify types of information such as planes and other features relative to these. In the FabPod, for example, there are 180 components cells, made up of over 1000 timber frame elements. The toolpaths to cut each of these parts have between 200 and 300 points. We would struggle to address this quantity of information without standards in modules and interfaces.

The relocation of standards from defining dimensions of parts to defining more diverse and complex types of geometric information has enabled a major shift in the forms we can design and fabricate. However, it has not removed the need for repetitive process and in some cases has encouraged a proliferation in the number of functions demanded across design and fabrication. With better means to manage complexity, we face new decisions around the quantities and types of differentiation we pursue.

8.2.2 Accommodating Future Uncertainty for Design Exploration

Beyond creating difference for its own sake, in the projects here I present a series of hypotheses around how architecture might perform. The workflows we have designed here are systems composed of a combination of specific tools and techniques. Through designing these workflows, we define domains within which we can accommodate uncertainty in order to explore specific design outcomes within useful limits, defined through constraints inbuilt in the workflow. The scope for exploration directly relates to the degree of modularity at each level of detail within the workflow.

In a first instance, we have accommodated uncertainty in the overall form and performance of the piece of architecture. At the broad scale of Divisions in projects I have already highlighted that form, performance and fabrication are only loosely coupled and impart loose constraints on one another. For example, in the FabPod, we were able to explore a range or materials and formal effects, constrained only by the need to use spherical forms. To a further extent, in the Music Room, the fabrication process combining robot with bandsaw related to both form and acoustic performance. By establishing low levels of modularity across a Design System we could explore a range of geometry without definitive constraint in panel sizes, materials or shapes.

Looking at finer levels of detail, we accommodate uncertainty through discrete interactions of Tasks and Functions. In digital chains for fabrication, we translate geometric information into instructions for a machine. It is possible to identify several levels of specificity in this process. A useful example from the projects lies in the fabrication of frames for the FabPod where the exact CNC machines for fabrication were only identified after the detailed modeling was complete. In response to this uncertainty, tool path information was captured in a generic vector-based format and later post-processed into two different formats for two machines to fabricate parts. Specific types of uncertainty is also accommodated through the flexibility of parametric models. However, as Davis and Peters describe, designers must be aware of the flexibility created and limited when defining relationships between parts. Ideally, this flexibility is correctly allocated, “the designer must ensure the relationships between components are flexible enough to accommodate unexpected changes” (p.131). At a technical level these models are dependency graphs which can become incomputable. In such cases, a designer is left with little option but to simply rebuild it (Davis, 2013, 5).

These different levels of detail frame two modes of uncertainty. Highly modular, ‘black-boxed’ systems are predictable in their function and are common in contexts such

as manufacturing where reliability and volume are essential. It warrants little explanation, however, that such systems are of limited use for design exploration. Conversely, while a fine grain of modules can enable flexibility, to many parts at these scales can be undesirable. Accommodating too much uncertainty which overly burden individual design decisions.

In the projects here, design directions evolved through the development of workflows. As such, the uncertainty accommodated was iterative reducedreduced. Initially, design was framed through concepts which established at the outset of each project. In the FabPod, for example, we established a system by which architectural would be composed of intersecting spherical elements. While these forms are sufficiently generic to enable a level of exploration of form and acoustic performance, further constraints quickly became necessary. We identified that spheres should all be a common radius and be combinations of concave and convex forms, limiting designers exploring certain responses. Later still, we reduced uncertainty in the design by identifying good arrangements for the entry and other key points around the space, using these to compose iterations of form.

Through this iterative narrowing of form and material in in designs here, many aspects of the detail of prototypes were certain before the form of the architecture. This runs counter to common design approaches in which a detail is iteratively added to a given form.

8.2.3 Parallel Work for Distributed Design

It is commonplace for architects to work alongside experts from other disciplines. A distinctive feature of the project work here, however, are the multidisciplinary teams working on design across all stages from conception to fabrication of prototypes. This demanded ongoing collaboration with design distributed across teams and design stages, with myself working at various levels of detail across almost all aspect.

I have already outlined many Activities which were led by various collaborators through the project chapters, which in many cases were undertaken in parallel. For example, in the development of the FabPod, parametric models for detailed models of frames were developed simultaneous to parametric models for designing spherical forms and tessellating cells across these. Further developed alongside were acoustic simulation models and techniques and processes to assemble frames. For the Sound Bites project, a shared Division was developed to enable collaboration between architects and structural engineer. Interfaces with this Division, we engaged in parallel Activities for setting out form, for detailed structural and material tests, and for fabrication processes. For the Music Room, four parallel strands of investigation were undertaken to design a new fabrication technique, spanning the programming of a robot, the design of the bandsaw blade, the design of a gripper and the preparation of blanks. Each informed the forms and patterns of panels, the selection of timbers, and the installation of the modular enclosing shell of the room. In each of the examples above, Activities of our modular workflows were dependent upon others. As such, beyond simply speeding the prototyping process, it was necessary for these to happen in parallel in order to inform each other as interdependent parts.

This parallel work is manifest in many tools and techniques which were co-authored by a range of individuals in project teams. Beyond these teams we used a further array of others, from the relatively rare tools from the *KukaPRC* plugin developed primarily by Johannes Braumann at the *Association for Robots in Architecture*, to larger software packages for the simulation of structures of acoustic. *Alongside* these are those made freely available through online communities, exemplified by Daniel Piker's *Kangaroo* plugin for *Grasshopper*. Further again are the tools and machines for fabrication, from simple hand tools to industrial CNC machines.

These tools and techniques naturally have many layers of contributors in their design, highlighting the distribution of design across scales extending beyond the project work here. This is not unique to the project work here, though it highlights a modularity of process which is inherent to the ways we work. Often this features a high degree of modularity in process, with the design of a tool distinct from its use. In other cases, such as the plugins shared among collaborators, the modularity is much blurrier as tools are developed and used in parallel.

Much has been written about the benefits of collaboration in design. An individual designer can impart only limited knowledge across the broad disciplines demanded by design, from structures to materials to acoustics. Similarly, experts in these fields will likely have limited understanding of systems for fabrication and the composition of form, in which I have strong experience. Distributing design across of expert collaborators is important to successful design outcomes and demands ready sharing of tools and techniques

Conversely, the sharing of tools and techniques inevitably increases risks as they are used by a broad arrays of users in many contexts. This is increasingly relevant to online communities creating and sharing tools. Where we might simulate an aspect of performance, for example, techniques can be easily misused and results misinterpreted without a deep understanding of their internal function. As a range of tools are increasingly accessible to designers, distinguishing between them in terms of their technical function is often difficult. Similarly, identifying how particular information has been created is presents many challenges. As such, harnessing the benefits of distributed design requires careful consideration of the degree of modularity at each level of detail in a workflow.

8.3 Key Issues of a Plugin Practice

In the previous section I related known purposes of modularity to key ambitions of design research. It is important to clarify that there is not simple causation. Families of differentiated components, for example, are not an inevitable outcome from a modularity of process. Nor do they cause it. Rather there are intricate relationships between the two. These reflect broader tensions between design practice and technology. I introduced some of these tensions in the Background chapter, including between serving and driving design, and across parallel practices of prototyping. I have also explicitly addressed each of these dichotomies in each of the major projects undertaken herein.

In this section, I build upon this background and discussion to frame a ‘plugin practice’, underpinned by a modularity of process. As I have already touched upon, in this practice we create specific tools and techniques as well as adopt and adapt those of others. Here I discuss two key issues of this practice, in order to enrich understandings of modularity in processes of design and prototyping, and to frame directions for future research. For each case, I refer both to key examples from within my project work and to emerging bodies of literature outside it.

A plugin practice explicitly requires us to consider how we calibrate a diverse set of processes with one another. Calibration is related both to the control of dimensional tolerances as well as the level of constraint in process which can enable design exploration. In both regards, process is manifest in the material prototypes. Alongside this are the ways we use, share and potentially create knowledge. Again this is multifaceted, related to knowledge created through design research such as this, as well as other forms of knowledge at finer grains. Finally, modularity of process invites us to consider the organisation of systems beyond the scale of an individual project. These are both broader, in the industry and economies around design, and finer looking at underlying logic and function of systems we use, both in computation and material craft.

8.3.1 Calibration and Tolerance

Through this research, I have worked with teams to create and appropriate a collection of tools and techniques, relating these to one another in Design Systems. In doing so, we both enable design exploration at an architectural scale and place constraints on possible outcomes. This is not to say that systems are overly constrained, and the projects demonstrate exploration through a broad space of such results. Often there is little precedent in the relationships between processes and little time to understand relationships in detail, reflecting the practice of prototyping pursued in this research. As such, these Design Systems sit in contrast to the systems of other fields such as computer science and manufacturing which are commonly refined to function in a predictable manner.

I have already discussed exploration of the interdependent aspects form, performance, and fabrication and material. At broad scales of process, between Activities, the calibration of these aspects is intentionally loose. For example, the acoustic simulations of the FabPod provided loose guidelines for the design of form and material. We made assumptions as to scattering coefficients of the various cladding materials and modeled hyperboloid forms as a series of triangular mesh faces. The large tolerances in these assumption do not provide conditions for detailed research into the acoustic performance, and such outcomes were not drivers of this research. Rather we were able to compare variations in form and material through acoustic simulation in order for performance to drive iterative design research. That over 500 designs were explored illustrated the flexibility in the system.

In contrast to this broad scale, the ways we work at fine scales are tightly controlled through discrete tolerances. We confront issues of calibration immediately in using digital modeling software such as Rhino and subsequently using CNC machines, which operate within strict tolerances. Looking once more at the FabPod, our cell components were modeled to a tolerance of 1/10,000 of millimeter, a rounding figure required for computing the underlying NURBS mathematics. The shapes of component parts were subsequently approximated as polylines within a 0.1mm tolerance, and trimmed by a CNC router operating at a similar tolerance. In manual fabrication, the accuracy and control of individual motions is similarly important and is dependent on the design and tools and jigs. A level of precision at this scale is immediately evident in the built FabPod with component cells meeting at controlled and consistent 3mm joints (Fig. 8.02).

Beyond discrete tolerances in machining parts, in fabrication we must further consider tolerances in multiple scales of assembly. Tolerance here is conventionally controlled through similarly discrete standards, for example through oversized holes in connection joints. When assembling components of differentiated forms, however, control of tolerances must be reconsidered in order to achieve an outcome in which all parts fit. The cells of the FabPod again provide a good example of this, with parts assembled to within a 0.5mm tolerance. Here cells were loosely placed and then connections tightened in parallel. In contrast, once the main cells were assembled, the exterior panels could be fixed in sequence and adjusted by eye. Beyond visual finish quality, error in this process has no impact on adjacent parts and overall form.

As we address processes of fabrication alongside design, we are forced to engage calibration of these multiple scales in parallel. A common approach is a duality, apparent in the projects here, between a loose calibration of process at a broad scale, and a higher degree at finer scales. This broadly reflects differences in the degrees of modularity of process and allows design exploration at an architectural scale and ensure a successful fabrication process at finer scales.

This duality, however, is not inevitable but rather presents a set of questions for architects which are only beginning to be considered in the context of contemporary technology (Sheil, 2014). From one perspective, it is challenged by some practitioners who use fabrication as a generative tool for design. I have highlighted such an approach in Section 2.1.1, though the generative design work and final production are typically distinct. From another perspective, a loose calibration of process at an architectural scale will be inevitably challenged where we which to refine systems. This could be driven by a desire to scale up manufacture. Similarly, in future research, metrics around

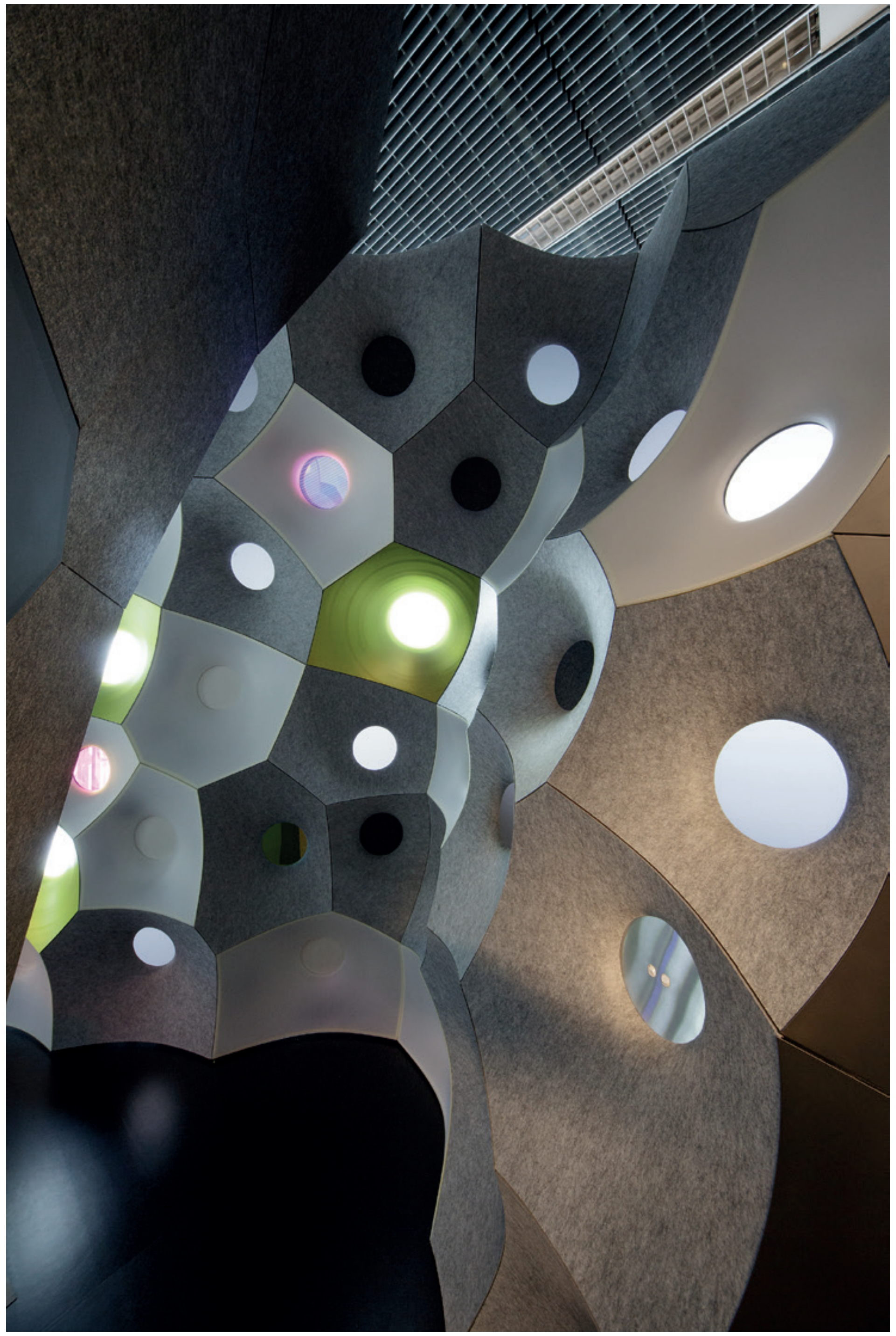

Fig. 8.02. The semi-open entry to the FabPod.

the performance of aspects such as acoustics and structures might take precedence, further demanding higher calibration with form and materiality of a design. Both of these reflects a practice of prototyping for industry which I have touched on in section 2.2.1.

Further emphasising a central role of negotiating tolerances, Branko Kolarevic demands that architects not forget the construction industry (2014, 131). In the “Beyond Novelty” of the Background chapter (Section 2.1.4) I highlighted that innovation and transformation of the construction industry are now in the sights of groups like the NCCR (Digital Fabrication) at the ETH, Zurich. While tackling such ambitions lies beyond the scope of a doctorate such as this, we can nevertheless speculate on what changes might be needed. These might occur either across the projects of individual design practices, across specific services offered by new types of practice, or alternatively across new types of customisable product. Changes of all three types are already apparent in emerging forms of practice (see section 2.1), and in the application of concepts such as mass-customisation to apartments (Piroozfar and Piller, 2013, 4). Beyond this are likely other forms and organisations, some of which are yet to emerge. In any of these contexts, the relationships between dimensional tolerance in material and the calibration of process are inextricable. As such, futures scenarios will demand that calibration of process be considered across these broad scales, and require us to consider modularity.

Kolarevic also highlights (2014, 130) that tolerances are associated with specific manufacturing processes and materials. These point to finer levels of detail than we have considered in the projects here, though we nevertheless engage with them. In an example such as a cutting process, the speed and trajectory of cut must relate to the shape of tool for the flutes to displace material to ensure ongoing cutting motion. Calibration at this scale of process is rarely considered by designers and negative impacts are typically considered as errors. With increasing control of machinery, we might imagine opportunities to more substantially explore calibration at fine scales as exemplified by the emerging work of practitioners such as the Soft Tolerance Approach of Marta Male-Alemany and Jordi Portell (2014, 122). Here, material deformation and a low level of control are being used to challenge current limits of generative design work.

8.3.2 Creating and Reusing Knowledge

In the Introduction of this dissertation, I outlined a series of perspectives on how knowledge is created through design. These cover Peter Downton’s observation that design creates knowledge about designing, to the importance of discovering new territory through design described by Nigel Cross, to the reflection-in-action approach framed by Donald Schon, highlighting that theory and practice interact in response to a problem. This body of theory underpins the value placed on design research in programs such as the one in which this doctorate is undertaken.

Through the project work I have further emphasised how knowledge can be created through the exploration of interdependent aspects of form, material, fabrication and performance. The Design Systems which I have developed do not prescribe outcomes or drive convergence to singular, optimal solutions. Rather, using these systems we can make trade-offs and identify sweet spots. This is a mode of creating knowledge which is specific to design and which is centered on exploration. Through exploring broad spans of possible outcomes we can deepen understandings of various aspects of architecture, from impacts of form, to the ways to perceive material finish and space. As I have already discussed, this demands that modularity at the scale of project Division is relatively low.

Through design exploration we also find opportunities to further create knowledge by challenging conventions in other disciplines. I have already touched on the research outputs in the fields of acoustics and anthropology which were created around the first FabPod prototype (see Section 7.4.1). While an architect might appear impotent in challenging the deep technical knowledge in fields, opportunities exist to make contributions through driving research into new areas.

Beyond these form of knowledge at a relatively broad scale, we can create and reuse other forms at finer levels. In the design and prototyping discussed here we are continually required to invent and adapt tools and techniques. Examples can be found throughout, from the combination of bandsaw and robot, to algorithms to approximate freeform surfaces with planar facets, to polygonal sheet metal frames which are laser cut and folded into a specific three dimensional form. In the taxonomy of scales used here, this knowledge resides largely at the scale of the Basic Task. At this scale, process needs to be precise in order to interact with other modules for design.

I have already discussed that the scale of Basic Task is a primary scale for automation and the ways we interact with knowledge at this scale is rapidly changing. There are today significant online communities which have formed around software platforms such as *McNeel Grasshopper*. Individuals share code as part of an extended toolset which extend and customise software environments. As I have already highlighted, these are often shared and used by others, with code designed to be highly modular for exchange and reuse. Such sharing of code reflects the shared authorship that is necessitated by the practices of design and prototyping and which I have discussed throughout the project work here. Beyond the bounds of academic research, such shared authorship through software code is becoming apparent in commercial practice as well. A global community of digital toolmakers is exerting increasing influence on design practice, with their algorithms nested in design process (Fok and Picon, 2016, 6). This challenges conventions around ownership and intellectual property as an individual's code is applied in a situation beyond that which they had considered when releasing it.

I have also already highlighted that shared authorship is evident in the fabrication of prototypes. Significant experience and skill contributed by colleagues such as John Cherrey, an individual who has many decades' experience making furniture and models. John led broad Activities such as selecting and identifying timber, involving a complex mix of first hand experience and knowledge of the specific marketplace. He also used his knowledge to design simple Functions for students to participate in making. This built on craft knowledge at finer levels, the expertise of which Is, at times, easy to overlook amidst a seeming ease of execution.

The aspects above demonstrate a breadth of ways in which we have extended and reused knowledge through the project work. This ranges from broad knowledge

of space and form created through architecture, to detailed and disciplinary knowledge in fields of acoustics and structures. Reuse is explicit in both the shared code of digital tools, and in the use of physical tools and jigs for fabrication.

As with the previous section, an image from the project material captures many layers simultaneously. A detailed image of Music Room wall panels (Fig. 8.03) shows timber elements separated by a 6mm gap. We see evidence of craft experienced applied to dress timber parts which are book-matched timber, the grain and colour of the panels mirrored either side of the gap. The parts are finished in a square cut despite visible variability in the anisotropic material. The rough cut texture of the timber faces provides a contrast, a finish which is imperfect yet controlled. Together these reflect a deep knowledge of material craft and the development of tools and techniques used to finish the panels. Alongside the apparent control of finishes, the image has a layering of colour and form which are accentuated by black curves running across the pieces. These curved, asymmetric forms and layers of material are unfamiliar and their control is evidence of digital simulation both in design and fabrication. This further reveals the design exploration which has underpinned them, which are driven by both aesthetic outcomes and acoustic performance.

In these multiple aspects of the image we can identify ways in which we have created and reused many types of knowledge in differing forms. This knowledge is at multiple levels of process, from that used to control the fine movements of tools and material parts, to the broader processes of defining form and colour. I have discussed five levels of process which I have appropriated from the taxonomy set out by John Everett (1991). Beyond these levels, Everett articulates finer levels of detail which underlying the Elemental Functions of our design systems. While I have presented Functions as discrete and robust modules, I do not wish to pretend that these cannot be further unpacked.

John Everett identifies that Orthopedic and Cellular operations underpin motions (1991, 71). Such control is extensively discussed in literature on material craft, highlighting muscle memory and skill of an experienced practitioner which develops

Fig. 8.03. A detail from a wall of the Music Room, showing two adjacent panels.

through considerable experience (Sennett, 2008, 20). Similarly clear are the lower levels of computer algorithm which underpin software tools. The computer programming languages we use for design are themselves built on further levels of code. Platforms such as Microsoft's .NET framework provide flexible and robust coding environments which provide modular code libraries. Concepts around the design of such layers of code are necessary to navigate and influence the ways we work.

Though finer levels of process detail are intuitively navigated by designers, they are rarely discussed amongst literature from the digital design and fabrication community. In this mode, craft has been used by many scholars and practitioners, though there is relatively little research which draws on the extensive literature around either material craft, nor the fundamental concepts of software engineering such as design patterns. Furthermore, little of it considers modularity at these scales. Future research in design can explicitly connect with the knowledge which is embedded at these scales.

In a similar fashion, knowledge of the broader scales of industry is intuitively considered but often insufficiently understood by designed. In a 'plugin practice' in which design is distributed across experts from a range of disciplines, architects will face challenges to conventional roles and services. There is evidence that modularity at the scale of broad services will play a significant role in shaping future industry. For example, in the computer industry which is the focus of research by Carliss and Baldwin, modularity is at the heart of transformation, "a financial force that can change the structure of an industry" (Carliss and Baldwin, 2004, 1). In today's architecture and construction industries, we see both a diverse series of small start-up companies offering new services, as well as a consolidation of larger contractor and consulting firms. There is much opportunity in both research and practice to further understand a modularity of process beyond individual projects, in order to better frame its role in future design practice.

9. Conclusion

It is more than 50 years since Plugin City was conceived by Archigram. This speculative proposal for a future urbanism contributed to debates about the future relationships of design, technology and society. In the years since, this vision of plugging modular building components into an infrastructure, promoted by Archigram, the Metabolist movements in Europe and Japan and many others, has endured a chequered history. Understandings of modular design are widely applied. However, significant gaps now exist between the modular mass-production of the prefabrication industry, and the interests of a design-focused architecture community.

Today's architects are well versed in creating, sharing and using a diversity of tools and techniques to reach beyond the conventional domain of their discipline. This is underpinned by a modularity of process, a modularity which sits in contrast to the modular components of Archigram. Here, modularity is apparent in the function of discrete processes, doing one thing and doing it well. This echoes practices from industries as diverse as computer science and automotive design, and in complex systems such as climate and economic models.

In this research, I have demonstrated a modularity of process across a series of projects spanning a broad spectrum of design and prototyping for architecture. In these projects, some modules are literally software plugins. Others plug digital machines into workflows. Others still embedding information into material through plugging together simple fabrication processes. In each case, the modules add functionality at multiple levels of detail and to varying degrees, with modular Design Systems created for individual projects which are both flexible and robust. I have represented process up to the scale of these Design Systems through a series of diagrams, mapping the level of detail and the degree of modularity in each.

Through articulating a modularity within a body of project work, I have identified key features of modularity related to multiple levels of detail and varying degrees. It is useful for a low degree of modularity to be employed at a broad level of detail, allowing us to loosely calibrate activities of designing form, tuning performance and fabricating material components. It is similarly important for details of process to be highly modular, providing consistent and reliable functionality. Between these extremes I employ modularity to varying degrees, nesting function with greater degree of modularity at finer levels of detail.

This modularity underpins a “plugin practice” with key features across the design and prototyping of architecture. It allows us to manage complexity which is necessary to the design and fabrication of differentiated components. It further allows individuals to work in parallel, allowing design to be distributed across a broad set of experts. Further again, it allows us to maintain a level of future uncertainty, thus enabling design exploration across interdependent aspects of form, material and performance.

Finally, I have framed two key issues into which we can gain further insights through a modularity of process. As we create workflows for design, we must consider the levels to which these are calibrated and the tolerances with which they can function. This must vary at different levels of detail, highly calibrated where control is needed and more loosely coupled to allow diverse processes to interrelate. Furthermore, we must be conscious of the depth and breath of knowledge necessary to design and utilise these systems. An architect will have only partial knowledge in many fields, and will have to reuse and create knowledge in specific cases when pursuing design. Both of these issues are directly linked to a degree modularity in process, and are manifest in many types of outcomes from design, both immaterial and material. Future research into the relationship between modularity and each of these issues would be of value to a community of researchers in architectural design and prototyping . Furthermore, future research could more deeply consider a modularity of process beyond the bounds of individual projects, adding to our understandings of both the fine grain of processes underlying design and the broad function of industry. This would benefit those in the design research community seeking to drive innovation beyond the disciplinary bounds of architecture with which we are familiar.

10. Reference Material

10.1 Bibliography

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10.2 Image Credits

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Appendix. A

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