Designing the design: establishing boundary conditions for designing parametrically

Lessons from architectural praxis

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

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Declaration

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

Andrew Maher

Date
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Chapter One  Introduction to the research

Imagine: a conference on computing in architecture, a presentation is being given from a representative of a large architectural practice describing their latest efforts in the area of computing. The presenter gives a broad overview of the firm, which is of a size that can employ, in addition to its architectural staff, structural and mechanical engineers, planners and interior designers. The achievements are first illustrated on a per project basis. The presenter states they are emblematic of the way the firm is changing its methods in light of the results of the computing systems they have employed. The presentation begins with the origins of change, which not unlike other practices, have come initially with software to cover the business and document handling systems of accounting and specification production. This is followed by the use of computation to view planning schemes where data from consultants and government departments is drawn together for design and visualisation. Tools developed for specific tasks are shown, such as locating the seating sight-lines within an auditorium and for calculating environmental loads for the sizing of mechanical air handling systems. Then, exemplar projects for high-rise buildings are presented to illustrate how these tools can used in combination for use on a project. Here, variations of proposed floor plans are optimised towards a target gross floor area. Each instance considers the number and location of elements in the floor layout such as stairs, lifts and columns. It also adjusts the structure and suggests how many floors for mechanical plant equipment are required based on the types of heating and cooling required. An estimated cost to build is then produced. This data is transformed into project knowledge, forming the basis for the building’s design.

It would make a spectacular presentation, especially as one of the high-rise projects was the hundred storeys John Hancock Centre in Chicago. That the building was completed in 1970 and the presentation was indeed given – over 40 years ago in April 1968 at the Yale Conference on Computer Graphics in Architecture by Bruce Graham of the architects Skidmore, Owings & Merrill (SOM) (Graham 1969).

Graham went on to explain in his presentation that the next challenge the firm was working on was a method for creating drawings with a mechanical plotter from the output of the computational process, for all the above was printed as text on sheets of paper. Drawings followed and were drawn by hand.

During the intervening period, it has been widely noted that architects could more easily produce drawings using computers, but the process to embed knowledge and intention into those drawings is only beginning (Bruegmann 1989). That the position described by Graham is one that the construction sector is trying to achieve again today is one example of why construction is described as a laggard industry when it comes to the adoption of technology.

The 1968 Yale Conference on Computer Graphics in Architecture was held prior to software running ubiquitously on desktop computers in networked environments – and seven years before the founding of the Microsoft Corporation – when firms such as SOM took responsibility for writing their own computer programs. Where they could, the firms
transferred their expertise into software rules to be given results in a dramatically shorter period than would have been capable by hand.

During the more than 40 year period since the computer was introduced to architecture, architects have had an ambiguous relationship with the adoption of the computing paradigm to practice (Bijl 1989). Computation proliferates in architecture as it does in many fields, especially where information can be explicitly stated and may therefore be more easily computed. The obvious candidates, essential to the practice of architecture – communication, specification and description of buildings – have been tackled with drawing, presentation and business software. In what can be described as a democratisation of computing, architects have had increasing access to more powerful desktop computers on which they can run commercial software, from companies such as Bentley Systems, Autodesk and Graphisoft to name a few, best developed to do what it is thought architects do. However the praxis of architecture, namely the translation of an idea into a design, has not been well catered for in terms of computation.

At the outset, it would not be fair to directly equate SOM’s use of the computer over four decades ago with a claim that it encompassed architectural praxis as the work that was presented – high-rise towers – was a building typology very well understood at the firm and one that could, as much as possible, have as many rules as possible translated explicitly into code.

The external forces that have driven change through the sharing of information in other disciplines and industries have simply not been present in construction. In manufacturing, for example tooling machines that were computer controlled were first developed in the late 1950s and these machines necessitated readable computer representations of the products they were to make. This requirement compelled engineers to develop digital geometric modelling and the code for machine control.

At the same time researchers have been able to densely populate design spaces, but the problems are rather constricted to the laboratory. This research considers what happens in practice, or the border between research and practice – architectural praxis.

More recently, another form of software in which geometric form is controlled through the definition of parameters and application of constraints has been adopted in architecture. It is known as parametric software and with its history in mechanical engineering, originally developed for the aerospace and manufacturing industries, it offers as many challenges as opportunities in its use in architecture. In fact one of the pioneers of computing in architecture, Charles Eastman stated: ‘The expertise regarding rules for parametric boundary conditions is not widely available and will become a growing area of research’ (Sacks, Eastman & Lee 2004).

The aim of this research is to establish some of the boundary conditions for designing parametrically in architectural praxis.
This research builds upon the work that Professor Mark Burry has undertaken for The Sagrada Familia church in Barcelona. Since the early 1990s Professor Burry has been using parametric software to describe the complex geometry of the architect Antonio Gaudí for the church’s continuing construction.

The project has been undertaken within the context of three-dimensionally geometrically complex or difficult building forms, with a major case study founded upon research carried out under an Australian Research Council grant at The Sagrada Familia church, thus the subtitle of this project ‘Lessons from architectural praxis’. Form that resists standardised methods of description inherently has the potential to elicit new methods of description, and this intentionally restricts the study from another major foci of the use of the computer in architecture today: the building as a comprehensive database known as the ‘Building Information Model’.

To achieve the above aim, Chapters Two and Three form a background study for the research. Chapter Two looks at the development of parametric design and considers it both as a mode of technology transfer and in relation to the notion of ‘process’ in architecture. Chapter Three examines the special role difficult forms have presented in architecture challenging accepted modes of representation and notation. This chapter introduces The Sagrada Familia church as the work’s major case study.

Based on Chapters Two and Three, Chapter Four presents the design of the research. The hypothesis and research question are stated. Chapter Four highlights the use and structure of case studies in the various fields of architectural praxis, namely practice, research and pedagogy. It also presents a summary of each case study used in the study chronologically.

Chapters Five, Six and Seven develop Chapter Four’s research design under three themes. Chapter Five deals with the preparatory work for designing parametrically. Chapter Six looks at the formed parametric model and considers in action, the boundaries of the design space and its potential as a collaborative tool to cross disciplines. Chapter Seven examines the outcomes of the case studies and draws implications for designing parametrically within the broader construction sector.

Finally, the study’s research is discussed in Chapter Eight with the application of findings. The work is supported with appendixes containing papers published from the research as well as detailed descriptions of the case studies.

A personal motivation

My own experience working on the Federation Square project in Melbourne has some bearing on the direction of this research. My interest in modelling for architecture began when I worked on this project for the Lab Architecture Studio. It compounded existing questions I had about how the profession operated in the face of new technology and change.

Federation Square is a collection of buildings surrounding a public square in Melbourne. It was a huge project that involved the addition of an entire city block to the city by covering over existing rail yards which continued to operate during construction. The centrepiece is the
public square which is surrounded by cinemas, galleries and commercial spaces.

The most striking feature of the project are facades composed of sandstone, zinc and glass. These facades follow a strict geometric pattern and the consequent effect is of the facades wrapping themselves about the buildings. The resulting shapes are a collection of ever changing non-orthogonal forms. These forms represented a challenge both to design and to describe the buildings.

Figure 1.01. Federation Square

There was very little time between winning the competition and construction. Thus the pressure to produce documentation surfaced early in the project. A managing contractor was awarded the tender and construction began before the design had been finalised and proceeded on a fast-track basis. At all times contractors were asking for information. The result was that the design team had to work towards delivering packages for trades, rather than designing the project as a whole.

The architectural effort was undertaken through a project office that combined the architects who won the project with an established local firm. At the early stage of the project resources were planned around a documentation process, half on computer and half on drawing boards, and the skill base of those recruited to work on the project was largely split this way. However, it quickly became evident that standard orthographic drawing, particularly plans and sections, were not going to adequately describe the vertically non-orthogonal buildings in this project. Modelling, both physically and digitally, became the dominant method of resolving the design.

My role was twofold. As a project architect I was responsible for delivering the designs of buildings, two to schematic stage and two through to construction. My second role was as champion for a co-ordinated three-dimensional digital model. This responsibility began when I was asked if I would investigate digital modelling and a method for working in three dimensions. The model for Federation Square was constructed in Microstation software from
the American firm, Bentley Systems, with their Triforma (originally from Belgium) modelling add-on. It was one of the earliest uses of the Triforma product and at the outset garnered interest and support from Bentley in Australia.

I developed a method for documentation. The office was divided into teams, each of which had one or two architects specially trained in, and who were dedicated to, modelling. As a modelling community we agreed what would be modelled and what would be left to those drawing in two-dimensions. Plans and sections extracted from the model were used by documentation teams to add additional detail.

The process took an enormous amount of effort and consideration for the task at hand. Due to the time constraints we tested as we produced documentation and as the buildings rose from the ground.

The work at Federation Square preceded my PhD research, and although I went to the effort of preparing ethics approval to use data from the project, once the project had finished it didn’t seem that the experiences could be adequately captured for the research. It did however leave me with three acute observations I have carried forthwith.

The first observation concerned the adoption of three-dimensional modelling to architectural practice. Not all the architects agreed with the idea of working with a three-dimensional model. I was surprised to find early on a movement within the Federation Square project office to cease using the model. This reaction arose, I think, because senior architects felt they had a lack of control. This was partly inspired by the distance to what fast became the digital ‘master model’.

The second observation was that the digital Federation Square model, as prescribed by the software, was focussed on delivering documentation. The model enabled us to get the buildings completed, but it did not help in expanding the design possibilities during the early stages. With the compressed timescale to which we were subjected we desperately wanted to test variations to design proposals, but each variation required a model rebuild.

The third observation centred on participation with the various consultants. It became obvious that the benefits of the three-dimensional model could be shared amongst the broader project team. I organised a presentation with the project’s main consultants. By and large they were impressed, however, as they politely explained, they had a twofold inability to work with and contribute to the model. The first was fees. They had only anticipated working two-dimensionally and could not afford to experiment with three dimensions. Secondly, they did not have access to the skills.

One of the engineers, also an academic, who attended my presentation suggested I contact Professor Mark Burry which has ultimately led to this study. As a researcher I have continued to present my work to practice and although there is more acceptance of the idea of modelling, the conversations still follow similar lines. Practitioners, are concerned about implementing new technologies, change in the workplace, the skills required in the offices – and rightly so.
Endnote

1 Chapters Two and Three form a background study for the research, each with a focus. A general literature review for the research was made as an editable online hypertext document (known as a wiki) - the location of the wiki is http://zwiki.sial.rmit.edu.au/personal/AMaherWiki
Chapter Two  Parametric design

Introduction

Chapters Two and Three form the background chapters for this study. This chapter introduces parametric modelling and locates it within the history of computing in architecture\(^1\). It relates this with notions of ‘process’ in architectural praxis. One of the long held ambitions for digital media in architecture has been to provide environments for working in ways more closely aligned with those based on traditional media, to capture design intention with greater fluidity and to then present a realm of possible designs for exploration. I claim that parametric design offers a platform for people to work together and digital modelling, through the use of parameters and the application of constraints, embodies the potential to propel computing in architecture much further from the delineation systems that have commonly characterised the use of the computer as an electronic drafting board.

The function of this chapter is to introduce the relationship between process in architecture and what process might be in architectural computing with respect to parametric modelling. The intention of this chapter is to discuss the application of parametric modelling to architecture through a broader notion of designing parametrically, and to introduce the implications of working parametrically in the praxis of architecture. This chapter refers to two examples of parametric modelling in architecture, one using dedicated parametric software and the other working parametrically in non-parametric software, to illustrate the point of the shift in design resource required to work in this way.

Section 2.1 defines parametric modelling. It discusses the mathematical notions of parameters, constraints and relations, and places them in an architectural context. Section 2.2 discusses what designing for parametric modelling might entail. It looks at parametric modelling as a movement from a product-focus to a process-focus. Section 2.3 explores the manner in which design for parametric modelling is structured around processes. It looks at hierarchies, assemblies and sub-assemblies. Section 2.4 examines the implications of designing parametrically in architectural praxis. One example is the relation between the effort expended upon processes and the standard scales and fees charged by architects.

2.1  Parametric modelling

Most architectural software used for modelling and drawing requires some parameter input for the creation of geometry. Geometric parameters are often dimensional, so at its simplest one could say of a line, *the parameter of a line is its length*. At the object level, by changing the values for a line’s length, a line of variable dimension is created. The ability to subsequently access an object’s database and alter parametric values distinguishes a system which can be said to have flexibility, over one which is static, and cannot be re-edited. This difference is referred to as either *variational* or *explicit* geometry.

To place a cylindrical column for example may require a radius \((r)\) and height \((h)\), the
cylinder’s location \((l)\) and its direction \((d)\). Typically though, in architectural software upon the definition of the geometry, the inputs have not been available again. Without the preservation of the data structure of the object, and for subsequent geometry that is modelled, there is also no record of the relationship between each object or part of an assembly. So if the aforementioned column’s parameters have not been recorded, or the association of the column with surrounding geometry which may have helped locate it, then further manipulation of geometric objects or assemblies will require the erasure of earlier geometry and new designs to be modelled. Without a preserved data structure the geometry is an explicit object and if any further changes are required the creation process is repeated rather than revised.

This cycle has provided much frustration with the dissimilarity between the workings of software and the way architects think about changes, as in the case above where one could imagine the following narrative in natural language – ‘the column’s height changed because the depth of the beam it supported changed’. A natural extension to this initial discussion is that objects often change in relation to something else (a column to a beam, for example). The manner of this change is now discussed generally, and then more specifically in 2.3.

The definition and manipulation of geometric objects through parametric expression affords variation in shape representation. This means that a form of the narrative of the aforementioned architect is constructed in a machine-readable language so that if the beam is altered in a model, his or her column will dynamically re-express itself according to its parametric definition. The column is, of course, a simple example. The location of columns could merely be an element within the greater narrative of an architectural design.

Modelling with parametric geometry is where it is ‘the parameters of a particular design that are declared, not its shape’ (Kolarevic 2003). In application to architecture, parametric modelling is a powerful computational concept that finds no predefined representational equivalent. This is because parametric modelling requires, at the outset, a design of its own – parametric design – the strategic pre-figuration of a schema to drive the model. This type of design is the concern of this research. Wittenoom has described parametric models as ‘models of realisation’, (Wittenoom 1999) and Burry (1996) has proposed scenarios for the adoption of parametric design in architectural practice, first evoked with speculative projects such as the Paramorph (Burry 1999). Building a parametric representation, or designing parametrically, is a complex task that requires a deal of disciplinary skill. If we think of parametric design as a platform for working with other people then it follows that the skills and complexities are multiplied.

In this study, parametric modelling through the use of a preserved data structure has been achieved through one of two methods. One method has been to use dedicated parametric modelling software in which the data structure is attained through recording of a sequence of actions – a construction history, which is thereafter present and editable. The second method has been to ‘parameterise’ geometry by linking standard modelling software with a programming environment – a generative process, which can be generalised as procedural
as the data structure is independently held in software code and must be run to generate the geometry. One method is not entirely independent of the other as the two methods can be combined. I have, for example, worked with programming in dedicated parametric software. Either way – the geometric constructs of parametric models in this study are accomplished by graphing the dependency of objects, using one of the two methods.

With reference to the aforementioned cylindrical column example, in a generative process each computational pass will request \( r \) (radius), \( h \) (height), \( d \) (direction) and \( l \) (location), either as direct input or from a table of stored values (located in a linked data structure such as a spreadsheet). Using a construction history method, access to \( r \) and/or \( h \) and/or \( d \) and/or \( l \) is offered through a history graph of values. In either method, by assigning new values to the parameters of objects, changes are transmitted and checked for internal consistency throughout the dependencies, resulting in variance to the form. Relations might be bound by constraints including the geometrical or algebraic relations between objects. In this way elements of the cylindrical column that may be under consideration by an architect can be varied. The height and radius can be increased or decreased and the location and direction (or inclination) of the column altered. It is possible to illustrate how privileging parametric definition over explicit shape representation in architecture profits the modelling endeavour. Through parametric expression the space of the design is conceived, which might be thought of as a design space.

**Computers in architecture – history**

The expression of geometrical objects through computation has its historical basis in the early 1960s. In 1963 the pioneering graphical computing research of Ivan Sutherland was published. Sutherland’s PhD research, known as Sketchpad, encompassed the development of a system for drawing, entered directly via a light pen to a screen. His work immediately generated much interest in many disciplines (Sutherland 1963). In 1964 the first conference on computing in architecture was held (Bruegmann 1989, p. 140)

Much of the subsequent research continued to emanate from the field which was then described more generically as computer graphics. The 1968 Yale Conference on Computer Graphics in Architecture discussed a broad range of topics from methods of inputting data into computers, to issues arising from the use of computers with regional planning and to the perennial issue of whether the computation can augment human creativity. (Milne 1969) In fact, I found a striking similarity between the matters tackled in the 1960s and conferences on computing in architecture today.

By the early 1990s, research in parametric systems was occurring in engineering, particularly mechanical engineering, although software with capabilities of more intuitive interactivity (other than solely dimensional variation) was still in its infancy (Roller 1991). The emergence of fully fledged parametric modelling environments can be understood as a relatively recent phenomenon, their growth over the last decade combined in part with the huge acceleration in processing power available in both graphics and computing.
The position of digital media in architecture is partly informed through the experiences over the past four decades of computing systems in practice, some ambitious like Sketchpad, but mostly acquiescent to the discipline’s dominant modes of representation. Bruegmann (1989) charted the influence of graphic communication as a dominant factor in the relationship between architecture and computing. Parametric modelling has arrived in architecture by a circuitous route. Thus its raisons d’être are still up for debate and speculation, and unburdened with the conventions of architectural representation.

**Parameters, constraints and relations**

To better understand parametric modelling I found it useful to consider separately, parameters, constraints and relations. The etymology of the word *parameter* is derived from the Greek *para* – beside and *meter* – measure. The origins of the word are geometric; in relation to conics, for example, it refers to the locus of the parabola. The mathematical definition from the Oxford English Dictionary concisely describes the way a parameter is used to express geometry in parametric modelling software as: ‘a quantity which is constant in a particular case considered, but which varies in different cases’. Referring back to the case of the parabola then, by varying its parameter a family of parabolas is represented, or in another way, a series of instances of parabolas of the parabolic equation are generated.

If considered in reverse, it is possible to say that many parameterisations can exist for a single artefact. When designing with explicit geometry there are often multiple routes to describe or create an object, though this multiplicity is of little consequence when the record of the path or decisions taken along the way is absent. The route is important when it is recorded because the actions taken to arrive at a point will determine the possible direction(s), or flexibility, that may vary from there on. Chang and Woodbury have taken this concept further, speculating upon a theoretical parametricised procedure for a reversal of the direction taken (Chang & Woodbury 2003). They envisage this in a similar manner to a common ‘undo’ command found in most software applications but which in a design environment would uncover alternative (but topologically legitimate) paths backwards through a design space.

It is important to note that the combinations of sets of values for the parameters in each of the parameterisations are ‘design space’ and determine the space’s flexibility. Referring again to Chang and Woodbury, a design space may encompass, within its domain, unique areas not bounded by those of similar geometry yet arrived at through different routes. This is why parameter definition, strategy, and the associated skill in defining an initial schema, becomes paramount.

Finally, there is a more general use of the word parameter, which is to define a boundary. This is a broader concept (not to be confused with ‘perimeter’) but not dissimilar to the internal conversation in the mind when drawing – when one might be considering the peripheral values of a parameter.
What is a constraint?

‘Much of what transpires in everyday architectural practice is directed towards establishing limits.’ (Cuff 1991, p. 239). Cuff describes the need for constraints as limits to what could otherwise be a process of endless discovery. Project constraints, are usually initiated through the functional requirements of a brief, and constraints of different classes could include site boundaries or solar access and, very often, the budget. The word constraint although commonly implied, is not widely used in architectural design terminology. The oddity of the term is its negative connotation; yet in reality design intentions are almost always constrained.

Constraints have the effect of limiting the number of possible alternatives and therefore giving boundaries to the design space. Geometric constraints are the most conspicuous constraints between objects in parametric modelling software – constraining the relationships between objects to be perpendicular, parallel or tangential, for example. An example at a building element level could be the desire to intersect two walls obliquely at a specified angle. If the position of one wall changes, then the angle between both ought be maintained. In this case the constraint, being the angle, might be better thought of as a ‘desire’ as it is the intention of the design to have the walls meet at a specified angle. I found it useful to consider ‘constraint’ and ‘desire’ to be paired concepts when considering parametric design. In fact, in design, ‘desires’ have the sense of expectation whereas constraints have been found to elicit that of confinement or fixedness (Heath 1993).

Sutherland used geometrical constraints to initially define geometry in Sketchpad, but notably, after their establishment they were not maintained to further manipulate the geometry. In 1982 Light and Gossard published the results of research to vary geometry through dimensional constraints (in dimension-driven systems), and in 1991 Roller proposed a method for capturing implicit geometrical constraints, as geometry was created, or on the fly (Light & Gossard 1982; Roller 1991).

Heath (1993, p. 12) contended that knowledge of constraints in architectural design is largely tacitly acquired, and their application within a larger social ‘constraint web’ is a determinant of design opportunity. So the designer looks to a pool of similarly solved problems and chooses, consciously or not, to follow the exemplars. Similarly, conventional architectural representation, from the application of fixed increments of scalar drawing measurement to the strict adherence of orthogonality of views, is constraint determining. Such adhesion functions to assist in the provision of a framework which contributes towards the identity of the profession. Innovation in design, therefore, might find encouragement in correspondence with a tolerance for deviation from a strict adherence to typology.

Cultural constraints such as pedestrian behaviour (keeping to the left or the right of others on the footpath, usually follows that of the driving rules in a particular geographic location. Norman (1988, p. 60) gives the example of the action of tightening a screw in a clockwise direction. The extent to which such constraints can find geometric equivalence in architectural form corresponds with one of the central pursuits of design and is one of the concerns of this
research.

Constraint definition, or elicitation, is an evolving and ongoing activity. The classic view of movement within a constraint model is that found through constraint solving. The application of constraints delimits the explorative space and, therefore, the ability to pursue exploration is related to the flexibility of the model and its construction.

**An example**

If the parameters and constraints are the constitutive properties of a parametrically defined design space, it is contingent upon the ability to build relations between the values assigned to parameters, and the application of constraints. Acquiring and then maintaining these relations are essential for parametric design, sometimes distinguished by the term ‘associative geometry’.

![Parametric relations - Inflating a ball.](image)

This example is a simple illustration of parametric modelling as it has been discussed so far in this chapter. Figure 2.01 illustrates three levels of parametric intervention of geometry. Here, in an abstraction, four objects are arranged to simulate the action of pumping air into a ball.

1 *The ball.* NURBS (Non-Uniform Rational B-Spline) based software that mathematically defines geometry provides an example of parametric recalculation of the ‘ball’ through direct manipulation of its control points. Some software offers limited geometrical interaction through control points that allow the designer, via the graphical interface, to grip or grab hold and manipulate objects. There are no constraints, and the relationships between geometrical objects are not maintained.
2 *The pump.* More advanced software retains parameters within its database for later value changes. Here, the length of the pump’s ‘tube’ is reconfigured as a parameter, and can be changed, although in isolation. This level of internal object parametric representation is beginning to emerge in conventional CAD systems and represents a level of data preservation for subsequent access.

3 *Pumping up the ball.* Through the association of geometry, this time, as the ‘handle’ moves, the tube follows and in unison the ‘ball’ inflates. In this case constraints are defined between the geometrical elements as well as the manner in which parameters varied. Here a non-linear function associated with the tube’s movement inflates the ball.

Designing relations between geometrical forms can be difficult and time consuming, although they are almost always easily described using natural language, such as in this example: *the ball should inflate in a non-linear way when the handle moves in the tube.* The task is to reformulate what often arrives in a commonsensical way to a designer, into geometrical and algebraic relations. This can be obvious, as with the earlier site boundary or solar access references. Solar access, for example, is defined through the graphing of the sun’s altitude and azimuth for a particular line of latitude. Less obvious is the symbolic transferral of the functional constraints of a brief which are usually communicated through the mediums of speech or written material, or socially or culturally defined constraints. Defining associations and making alterations, without enduring the cycles of deletion and re-creation, corresponds much more closely with the process of design decision making, and ‘the ability to explore a continuum of design states represents a fundamental advance towards using the computer as a medium’ (McCullough 1996).

**Context**

Although the cornerstone of parametric modelling is geometrical, context is fundamental. After all, what is an architectural parameter, and what is an architectural constraint? No ‘off the shelf’ tool is going to necessarily capture the possibilities or the intentions. Working in this way requires both the identification of what is architectural and the ability to transfer that knowledge to an algebraic or geometric equivalence.

To the organisational and systems theorist, Herbert Simon, the design of an artefact was deemed appropriate at the interface between the artefact’s ‘inner environment’ (its internal organisation), and its adaption to its surroundings, the ‘outer environment’. The mediation to that point was through the design process, characterised by the *constraints* of the inner environment and the *parameters* of the outer. Solutions emerged from the satisfaction of the relationship between the inner to the outer (Simon 1969). This view presents design as internally knowable but complex in adaptation, or by version. In an architectural application, Hillier gave a relatively contemporaneous example to Simon of unfolding an internal system (the kit of an army on the march) to an outer environment (the setting up of each new camp). The similarities between sites were termed an ‘instrumental set’, being the way in which
equipment was assembled, whereas the differences were environmental and tacit – and no doubt influenced by self-preservation (Hillier & Leaman 1974). Perceiving the contextual relationships between parameters and constraints is rudimentary to design parametrically.

### 2.2 From product to process

The scientific study of the activity of designing is a relatively recent area of research. The gaze of the architect is naturally inclined towards the object, as Cuff (1991) reminds us that the architect’s response to a brief is not likely to be anything other than a built structure.

I have found the work of the philosopher, Nelson Goodman, to be very useful. Goodman (1968) believed architecture stood outside a formal notation. Architecture was a “mixed case” as he saw it, located between the *allographic* and the *autographic*. This view was largely formed by architecture’s reliance on the sketch, emblematic of the continuous link with the author. Goodman identified the reluctance to separate a building from its design (by recognising each instance of a work as architecture) as the exemplification of architecture’s weak notational language. Robin Evans, too, noted the sketch as a special condition, given greater prominence during the 20th century, speculating that architects perhaps published them to illustrate a continuance between conception and construction, and also to give ‘proof that Art was afoot’ (Evans 1989). The process of translation from sketch to working drawing is a move between the private and the public consideration of a design. The continuity between these types of drawings (they generally fall within the canon of architectural representation) is disturbed as the media, tools, and tacit rules change during the design process. This re-presentation constitutes some of the distinct qualities of the architectural enterprise and its praxis.

Therefore, the notion of recording design processes, through parametric models, is a radical departure from both the way architects design and the way they conceive the design. Even the narrative of the process, at the culmination of a project, tends to shortcut the path of discovery as architects describe the design process as a linear chain of events: ‘this happened, then that, so we did this...’ (Steele & Macmillan 2001). While probably consistent with most human reflection as distinct from reflective practice, empirical research suggests, it is much more likely to include a generate/evaluate cycle, elucidated through honing a solution within a finite period. Zeisel (1984) used a spiral metaphor to describe the design process, while Archea (1987) depicted the process as ‘puzzle-making’. The linear recollection is quite likely to contain cycles of research, observation and reflection that in practice are not always recorded.

Archea’s thesis was ‘that architects work in a manner that is antithetical to problem-solving because they cannot explicate desired effects prior to their realisation through the design process’ (Archea 1987, p. 37). He argued that professional fragmentation perceived in the building disciplines was in fact a segregation of elements of building design into those that could be defined so as to be ‘problem-solved’ - structural engineering being the first new discipline.
Tom Peters (1992), in this regard, suggests the proclivities of architects and engineers can be discerned through the illustrations in their professional publications. He observes that architects prefer to be shown ‘new and pristine buildings’ focussing on what can be built, whereas engineers’ publications show ‘sites at work’ concerning themselves with ‘how a given design can be realised’. This can also be linked to their respective working methods. Engineers are required to preserve the reams of calculative processes to justify their decisions as they are made through the symbolic structure of mathematics. Architects’ drawings, on the other hand, describe the finished building, but not the process by which the design arrived. It is only, according to Robin Evans ‘in some cases, necessarily rare, the imaginative intelligence of the architect is divided between the drawing and inventing the thing drawn’ (Evans 1989, p. 21).

The view of Bijl – that ‘experience of design shows that the same task, viewed after a time interval of years, is likely to exhibit a different formulation and execution - the task will have evolved’ (Bijl 1989, p. 70) – is reinforced by the more recent work of Steven Groák (1998). Groák, who was at the time of his death in 1998 benchmarking process representation from various industries, had formed the opinion that ‘in construction I am increasingly convinced process is more unique than the product. The evidence shows uniqueness in construction to be in the process’ (Groák 1998, p. 57). This uniqueness is certainly privileged in architecture.

The attempt to rationalise process in architecture through “design methodologies” largely failed in its rigorous effort to explicitly and scientifically formulate design processes. The real damage suffered by the protagonists of a rationalised scientific view of design was that design seemed continually to escape definition. A set of procedures for one problem could not be rationalised in such a way as to suit the next, and so forth. Experience designing parametrically so far suggests that models intrinsic to a particular project’s processes are not easily applied outside their specific design space. It is rather the knowledge gained through strategic schema formulation that is carried forward.

### 2.3 Designing parametrically

A parametric model differs from many of the tools used by architects in that both the organisation and an interactive recording of a design process take place. Recorded and a record, process is not only privileged, but preserved. This inverts the traditional fixation of architecture on the object, to the processes of its generation. Objects become instances of the parametric model. What transpires when designing parametrically then can be understood as meta-process – the process of the process.

#### The design schema

In parametric design, prefiguring a schema is the method for defining the possible design space. This two-stage process was described by McCullough as ‘composing a structure, and then exploring the consequences of that structure’ (McCullough 1996, p. 229). A schema is not only the binding of what is known with what is partially known; importantly, it is also an
attempt at predicting the design space.

The prospective ability to foresee change and then to further adapt is in part constituted within the schema through the assimilation the designer’s mental model - or design intent. This externalising of the process of design has its parallels in architecture with sketching and study drawings, and with computing in the field of cognition, particularly in the cognitive systems research known as Situation Awareness. Situation Awareness is used for the construction of mental models to support human decision making where large amounts of data are available, and has been defined as ‘the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning and the projection of their status in the near future’ (Endsley, 1988).

In parametric design, it is the determination of pertinent parameters, constraints and relations for a design, or a space of designs, that result from both the information at hand and the mental model of the designer. Media for schema description and representation incorporate both the discursive and non-discursive: physical models, diagrams, and spoken or textual form. The criteria for usefulness in a parametric model would be that some aspect of the design intent is rendered explicit.

The schema, as both a structure and a processor, commits the designer early in the design process to the conditions for an acceptable design, and requires a more precise quality of disciplinary skill. ‘The expertise regarding rules for parametric boundary conditions is not widely available and will become a growing area of research’ (Sacks 2003). The relationship between schema and parametric model is continuous, and through this research I believe it is possible that schema definition for architectural computation could in fact become a specialisation on its own. Heath observed Peter Eisenman’s use of geometric constraints in traditional media as lying between the tacit assumptions of a design program and a project’s active decision making – rather the rules for the ‘reschematisation of the design task’ (Heath 1993, p. 84).

A schema is not limited to being constituted by more than one designer, which raises the question of authorship. Burry (2003), commenting on the parallels with other industries, has proposed the structure of parametric design as one for team collaboration, where the authorship is shared between the participants of the design process. While the most obvious candidates might be found within the circle of consultants that architects frequently use, there is a natural extension to those not normally associated with defining design, yet who do implement many of the constraints architects must work with: including clients, project managers and user’s groups. The notion of acknowledging the intention of more than one author is one of the more radical kernels contained within designing parametrically. Yet, although known to be the way a building is designed, multiple authorship should be recognised as a double-edged sword to the conflicting view that the potency of a work of architecture is associated with, and inseparable from, a single, identified author.
Methodologies and computing

When designing parametrically, well executed variants, (regardless of whether historically or generatively created), exhibit a level of schema abstraction that Mitchell (2003) describes as a ‘sophisticated piece of programming’. This abstraction is essentially exemplifying the shift from pre-determined structures and interfaces that have precluded the designer from stepping ‘outside the bounds of the computer application as conceived and implemented by the programmer’ (Bijl 1989, p.108). The opportunity for increasing interaction also changes by magnitude that which computing can offer for reflective practice, which Schon described as being bound by the ‘action-present, the zone of time in which an action can make a difference to the situation’ (Schon 1983, p.62).

Designing parametrically sublimes the broader research question of the amenability of architectural design to computing, and vice-versa. Computers as logic machines are founded on executing routines that are declared logically, whereas architecture, additionally, embodies values and judgements that are imparted tacitly through the process of design. The basic difference can be described between the two types of knowledge used when designing: declarative (or propositional), and procedural. Norman (1988) has observed that declarative knowledge - knowledge of can be easily transcribed and taught whereas procedural knowledge, knowledge for, is more often subjective, sensed and garnered through specific experience of a situation, which renders it difficult to describe. The extent to which design rules can be made explicit signals a limiting factor to the parametric embodiment of design intention, although when working parametrically, revision through the application of procedural knowledge becomes discernible.

In computing, the explicit/tacit conundrum is the province of Artificial Intelligence, the realm of mixed initiative that proper human-computer interaction might some day offer. Computing has so far been highly effective where there are known structures to replicate; the existing process of accounting and approvals system of a bank, for example. However, systems where decisions are made outside clearly defined boundaries have proved resistant to simulation by computation. This resistance has been particularly evident where there is exhibited an amenability to tacit expression, such as the ability to append meaning through annotation either as an alternative or, within the margins, in a supplementary manner. The use of traditional media in architecture falls into this category, as does another well-cited example of air traffic controllers (Sellen & Harper 2002) who make decisions from a variety of sources, one being information scrawled on paper lying strategically about the visual periphery of their work environments.

Designing parametrically requires thinking similar to designing with study drawings, but working in a dissimilar manner. No media is neutral, and parametric modelling is not exceptional in this regard. It is in acknowledging a mutualism that combines these forms of knowledge, of externalising the rules inside the designer’s head and arranging them with relation to the more formal constraints of a project, that further casts interaction with
the computer towards that of a medium. In this regard it is significant that a designer’s engagement with a parametric structure is not influenced by some reasoned computational process, but rather by a structure created through the transfer of the design schema.

2.4 Working parametrically

Architecture is a discipline where projects are almost always founded on partial knowledge and is necessarily iterative as that knowledge is supplemented, a process Archea (1987) characterised as ‘puzzle-making’.

Whether it be sourcing information for a schema that would normally be produced towards the end of a project, possibly with shop drawings, or identifying the processes of an allied discipline, designing parametrically challenges the way architects work. Working parametrically is not just the reordering of current procedures, it includes the direction in which the model is explored and searched to produce objects.

Process direction

Sketching would usually be considered a ‘top-down’ process. That is, it is understood as conceptually driven. The contrary direction is from ‘bottom-up’, being a data driven process. An initial reaction might be to identify the sketch and a view of architectural practice as a ‘top-down’ activity, though God, as Mies van der Rohe said, is in the details. Architectural design, as with many other design activities, propagates from both directions. This occurs naturally and simultaneously (though not necessarily at an equal pace) throughout a project, often finding a consistency with the availability of project information.

Design intention can vary the weighting between a ‘top-down’ and a ‘bottom-up’ approach. In my observation, some architects focus on details, refining connections over several projects – even a lifetime. Detail guides are often kept in offices and digital libraries are established to insert a practice’s custom solution where required. The functional requirements of projects can be framed around their detailed resolution – ‘bottom-up’. Architects who prefer to refer to manufacturer’s details or accepted building practices to finish details can, on the other hand, pursue a project much further in a ‘top-down’ manner.

Conventional architectural software does not generally offer tools for ‘top-down’ design. Instead, although the process might be directed from ‘top down’, it is driven by assembling components in a ‘bottom-up’ manner. This point of difference might be best illustrated with the correlation of the subtractive nature of conceptual modes of representation, such as block models with construction documents which exhibit both directions with elements such as grids, beginning with overall dimensions, but drawn line by line. By contrast, the adoption of digital media has gone together with fundamental organisational changes in the manufacturing sector where parametric software has been developed. Groák (1998) questioned whether the uniqueness in process that characterised the design of built structures had effectively inhibited the development of high level software for architecture.
Chapter Two

The fundamental difference to be found in the application of parametric modelling in industry is that original equipment manufacturers (OEM’s) ‘own’ their processes. This ownership is not literal, but rather the exertion of process control from conception to delivery. Suppliers, often geographically dispersed, strictly adhere to OEM’s systems and standards to supply modules for the assembly of products, and organisations and their software reflects this.

‘Bottom-up’ processes in manufacturing are evident within the specialisms associated with the design of parts of the assembly. The critical variables for a parametric description of a vehicle’s radiator might be the dimensional position of the locating bolt on its bracket. While a team of engineers consider the cooling system, at the end of each day it is a central database repository which notifies any other interested parties of changes in the locating bolt. As vehicle manufacturers share automobile platforms on a global basis, changes to a Ford design in Australia can affect another team working on an adjoining part for a Jaguar in the UK. In these cases, the association of geometry does not necessarily span across parts in an assembly; rather the database acts as a point of mediation, providing a way of manufacturing complex objects.

The processes in vehicle manufacturing feed up to distinct boundary conditions defined by clay models, or more recently digital versions of clay models, known as digital bucks. The agglomeration of separate parts is known as a digital mock-up. Boeing famously developed the 777 aeroplane as a digital mock-up and it is this possibility to compress time – from conception to delivery – which drives much of the investment in digital media for manufacturing (Sabbagh 1996). OEM’s are benchmarked by the time they take to get products to market. The benefits are to be found in economies of scales, the profits from the sales of repeated units of a manufacturing project amortise investment in design – an almost inverse relationship to architecture.

As technology transfer is one of the access routes to designing parametrically in architecture, the methods in manufacturing are well established and worthy of research, and their move to modelling with digital media is fundamentally linked with the knowledge base about which organisations are now structured. There are calls, such as those from Kieran and Timberlake (2004), for architects to become more like ‘process engineers’. The differences though are still acute. If manufacturing is thought of as assemblies of parts, then building by contrast could be conceived of as the accretion of processes.

Scales, particularly fees

In my experience, when presenting parametric design research to practice, two responses are common. The first overwhelmingly is concerned with how designing parametrically is accommodated within the fee structure and at what stage of a project does it begin. The second response supposes a parametric model has been established and queries the hierarchy of beneficiaries. For example, if a practice can well describe complex steelwork, is there likely to be a shift in both skill and financial resources to design from work normally
undertaken at shop drawing stage?

Currently in architecture, full fee projects are loaded towards where the tangibles occur. Construction drawings, which constitute the tangible artefacts of the design, are where the bulk of the fee is derived. In this way it is not uncommon practice to subsidise design work and make up the difference during documentation. To begin to speculate about the possible impact on architectural practice through working parametrically, the following two figures have been delineated. These show the recommended decomposition of a full fee structure in Australia, coupled with patterns of project interaction adopted from those empirically recorded by Cuff (1991). The two shown, between architects and architects working intra-practice, and architects and contractors, represent the greatest change when designing parametrically, particularly when structuring a parametric schema.

Figure 2.02 Typical interactions compared with full fee structure.

Cuff noted that over the length of a project an architect’s levels of design interactions were higher than any other participant in the process, requiring consistently high levels of co-operation between the participants throughout the project. The dips between the different stages illustrate what is often the juncture between modes of representation permitting short periods of relative autonomy. The most intense periods during which architects work together formulating a design do not generally coincide with interactions with contractors, who are traditionally introduced to a project either during tender or through construction. Then, interactions between contractors and architects are usually limited to approving shop drawings or answering questions arising from site.

Designing parametrically impacts upon that situation. The prefiguring of most parametric schemata occurs in the Design Development stage of a project. A ‘top-down’ schema would begin more closely to the schematic design stage than a ‘bottom-up’ schema. This process would broaden intra-practice co-operation to include new specialist participants within a practice who contribute to a project’s parametric definition. Participants might include mathematicians and programmers. Peak intra-practice design interaction would transfer from the Contract Documentation stage to Design Development, with the period of autonomy likely remaining after Schematic Design, mediated by the extent to which the parametric schema could be prefigured ‘top-down’. Activities such as three-dimensional scanning of physical models might take place at that point. The second period of autonomy would give way to a
less intense period of interaction as the parametric schema was transposed to a parametric model during Construction Documentation.

Figure 2.03. Possible interactions and fee structures when designing and working parametrically.

Along with the intra-practice interactions, other participants can offer input to the construction of the parametric schema. Most notable is the influence of contractors at an early stage. Their input might be in several short bursts throughout the Design Development of a project. This may be to determine design constraints and the methods of representation for output from the project model during Construction Documentation.

When designing parametrically, a greater emphasis is placed on the Design Development of a project. The shift in the fee structure towards recognising design as a process, which is tangible, ought to expand for schema creation and decrease where less effort needs to be expended, either due to automation in Construction Documentation or to improved communication in Contract Administration.

Although traditionally the generation of construction documents has seen the most fees devoted to it, with the establishment of a parametric model I could imagine the division between developing the design and reporting the construction information becoming blurred and the two stages merging as one.

Digital fabrication is a term which has been used to describe a broad activity that often exhibits the results of mass customisation (Mitchell 2003). However, whereas mass customisation refers to output with varying attributes (within the realm of a manufacturing procedure), digital fabrication is often one off. The difference, when designing parametrically, is that unlike using digital fabrication as a specialised contractor who builds from documents or files, fabrication information is used to inform the process through parameters and constraints. By comparison, Cuff’s empirical research on the patterns of interaction throughout an architectural project shows very little contact with contractors and the conclusion can be drawn that there is a minimum interchange of ideas or influence before the period of tender negotiations.

Construction (or fabrication) information is already implicitly embedded within the decisions made during the design process. This embeddedness is often expressed in units such as walls
built to brick and block lengths. Some conventional architectural software makes available stepping procedures so that lines are constrained to unit lengths (although the subtleties in the system are usually not expressed in the tools – for example, ‘unit lengths’ cannot describe a wall as being ‘the sum of unit lengths minus one joint’. If this tacit knowledge was to be embellished for the requirements of digital fabrication, say for computer numerically controlled machines, effort must be expended in order to achieve expressible procedures that could be used to influence the design process and the documentation requirements. This level of co-operation requires a shift in both fee and contract structures.

### 2.5 Conclusion

I believe that designing and working parametrically could be well suited to architectural design. Pre-figuring a schema and then testing proposals iteratively in model form can be performed in a way that is generally considered analogous to the process of design.

The translation of design information amenable to geometrical and analytical equivalence is quite possibly a higher hurdle in the earlier stages of design, as is the absence of graphic conventions for modelling. The reward, though, is a record of the design process for each artefact and the flexible encounter with its corresponding design space. The challenge, and this is a challenge for any interactive digital media, is to uncover corresponding ways of working.
Endnotes

1 Research in computing and architecture is fertile ground. Working in the area and attending, presenting and refereeing at international conferences has exposed me to much of the current research activity and community. The intention of this research is not to survey the breadth of current activity but rather to delve into its history, particularly its history from the 1960s-1980s.

2 Bruegmann recounts a twenty five year history of the enthusiasm for computer graphics in architecture. He places the first conference on the subject at the Boston Architecture Centre in December 1964.

3 Goodman separates authorship and execution with the allographic arts, such as music where the notation of musical scores, for example, can be discerned from an art such as sculpting in which in most circumstances, authorship and execution are united and without notation – the autographic.

4 Page numbers are not available as this is an electronic journal.

5 Cuff originally recorded five design interactions, but only two are recounted here. The patterns were originally intended for relative self-reference between types of design interactions and no vertical scale was set.
Chapter Three Complicated forms

Introduction

I suggested in Chapter Two that parametric design necessitated designing parametrically, which places a greater effort earlier in the design process. Chapter Three locates the development of the use of parametric design in architecture in the case of The Sagrada Familia church in Barcelona. My research was funded by an Australian Research Council (ARC) grant to extend the use of parametric design at The Sagrada Familia.

The function of this chapter is to provide background relating to the major case study of the research, The Sagrada Familia church, and also to consider the building’s role within the domain of non-standard buildings constructed with complicated forms that give resonance to the use of parametric modelling to aid their understanding.

To do this, Section 3.1 introduces the research at The Sagrada Familia and discusses how and why parametric modelling has been used to further the continuing construction. The work of the church’s most famous architect, Antoni Gaudí, is briefly discussed. The section also explicates the role of the ARC grant. Section 3.2 discusses how complex forms have historically required new methods of representation and construction, and how opportunities are raised when both representation and its notational structures are challenged. Examples from manufacturing industry, from where the technology transfer of parametric design is occurring, are given in Section 3.3.

3.1 The Sagrada Familia church in Barcelona

The continuing construction at The Sagrada Familia church in Barcelona is the subject of university research at both the Universitat Politècnica de Catalunya in Barcelona and RMIT University in Melbourne (Fig 3.01). Both universities work with the church’s Technical Office which operates on the site of the church not far from where the architect Antoni Gaudí had his studio.

The history of The Sagrada Familia church (1882-) is inextricably interwoven with the life’s work of the architect Antoni Gaudí and, in particular, another church he worked on during an extended design period that ran for almost a decade prior to the first stone being laid in 1908 – the Colònia Güell church. It was for the Colònia Güell that Antoni Gaudí developed the famous funicular hanging model he used to arrive at the unique solution for the form of the church. Although only the crypt for the church was completed, the derivation of form and the synthesis of structure and model are unmistakably evident and many argue found expression in the complicated forms of the much larger Sagrada Familia church (Tomlow 2002, p. 29).

The works of Antoni Gaudí were, and are, sites for testing and experimentation and while the dominant and popular view of Gaudí is that of the isolated genius (Gill 2001), such belief often overlooks some interesting and potentially illuminating developments in science and mathematics of his time. The funicular model, a three-dimensional model of cables hanging
under their own weight and constructed from cord and small bags of lead, owed a debt to graphical methods of analysis taught to engineers and architects of the time, as well as model making for mathematical instruction in the late 19th century (Collins, George R. 1963, p. 70). Both were intuitive methods, used by mathematicians and engineers to investigate increasingly ambitious concepts in their respective fields. Mathematicians’ models were generally constructed from string, plaster or wood, and used as visual aids for instruction, while engineers, utilising graphic statics, were able to investigate forms not easily analysed before its introduction.

For Gaudí, the combinatorial effect of these methods was the ability to affect variability in form through an empirical fusion of simultaneous representations. His now famous funicular model was in fact a three-dimensional version of graphic statics; the lead weights represented structural loads and the cords the resultant forces – providing a forum for a mutually dependent cross-disciplinary collaboration. As a tool for communication, it also recorded a dialogue between Gaudí and his assistants who would, upon instruction, shift the lead about to vary the shape and, located on site, it eventually served to convey construction information to the builders.

Figure 3.01 The Sagrada Familia church in Barcelona.
Parametric modelling and The Sagrada Familia

Research using parametric modelling had its genesis during the mid 1990s. My supervisor, Professor Mark Burry, presented the first case study of parametric modelling at The Sagrada Familia in 1996 (Burry 1996). The study presented an investigation into one of Gaudí’s extant modelled forms for the church, until that time only ever realised at scale in gypsum plaster. Burry emphasised that parametric modelling was used specifically for design development, pressed into service to ‘search for an effective solution to an unusual but defined design problem’ (Burry 1996, p. 73).

Burry, a Gaudí scholar, had at the time of his 1996 paper already spent 17 years working on The Sagrada Familia and had produced many drawings of the church’s complex geometry (Burry 1993). The subjects of the paper’s case study were the columns of the church’s triforium. The triforium is the gallery above the church’s nave. Burry’s referral to the design as a solution to a ‘defined design problem’ was a reference to the adherence of the parametric model to the codex of ruled surface geometry which Gaudí is known to have worked with during the last twelve years of his life as his material representation of the surfaces of the church.

The use of parametric modelling fulfilled three important functions at The Sagrada Familia. The first is that there is a ready correspondence between the mathematical order of surfaces Gaudi used to compose his building elements and their geometric reconstruction in digital form. The second is the ability to interactively engage with the parameters and constraints of Gaudí’s compositions. Burry’s paper revealed the parametric use of these absent points or ‘virtual points’, to control the composition of the triforium columns. The third is representational. Gaudí’s complex forms, whether of his earlier free-form works or the later using ruled surface geometry, were all studied in three dimensions, usually with scaled models in gypsum plaster. Where form was required to be wrested from a plane, Gaudí was not inhibited by the restraint of a drawing, either in provenance or in execution. ‘In his later career he relied more and more on models and mock-ups to [visualise a project in its entirety]; in a sense his drawings became a preliminary, or supplement, or merely a two-dimensional projection of the idea for the benefit of his public.’ (Collins, George R 1977, p. 15).

Each of these functions will be expanded upon in this section in relation to The Sagrada Familia, after an explanation of the role of the ARC grant. Then, in subsequent sections, I will expand the work of The Sagrada Familia to illustrate how complex forms in architecture provide and opportunity for new methods of representation, such as parametric modelling, and show similarities with industries outside the construction sector.

A note on the ARC grant

My research at The Sagrada Familia was undertaken through an ARC Strategic Partnerships with Industry (SPIRT) grant¹. The grant was entitled New onto Old: Flexible 3D computer modelling to aid heritage building restoration, recycling and extension (Burry & Datta
The grant’s aim was to extend the research at The Sagrada Familia that used parametric modelling to include the parametric modelling itself, by testing the flexibility of a parametrically designed model to accommodate the assumptions that must be made where accurate measurement is not possible. The research was to be centred on examining the first connection between the work based on Gaudí’s final forms (those scaled in gypsum plaster models) with the fabric of the existing building. ‘Work since 1978 has been dedicated to completing the nave and it is only now that the issue of connecting the new with the old has come to the fore’ (Burry & Datta 2001, p. 2).

The research was undertaken through a case study for the church’s roof and its connection to various elements of the existing structure. The new in the research title referred to the roof, corbertes in Catalan. The roof was designed by Gaudí in a modular format and one of the original models proposed for the church’s central nave and transept roof had been restored and shipped to RMIT University in Melbourne (Fig 3.02). This model is fully described in later chapters. The old were elements of the existing building, particularly the transept façades which at the time were not within reach of scaffolds on site and were without accurate drawings or records of construction. Of particular interest was the Nativity Façade which was built during Gaudí’s lifetime but still drew heavily on the neo-Gothic origins of the church, thus predating his forms of ruled surface geometry with which the roof was composed (Fig 3.03.).

Figure 3.02 The Corbertes model, a module for the roof of the nave and transepts for The Sagrada Familia church.
The grant intended the findings of the research to be of a wider appeal than confined only to The Sagrada Familia church:

‘the situation investigated here, though singular in itself and for a singular building, nevertheless represents an extremely common situation’ … ‘we expect that research, application and benchmarking the effectiveness of 3D computer modelling will provide unique insights into the potential for reiterative parametric modelling techniques for the construction industry’ (Burry & Datta 2001, p. 2).

SPIRT grants include industry partners and it was the Technical Office of The Sagrada Familia that co-sponsored the research, providing access to Gaudí’s original models, to workshop drawings and the site.

**Antoni Gaudí and the genesis of his complex forms**

The architect Antoni Gaudí (1852-1926) is now a figure of global popular culture, both identified and rejuvenated with the city of Barcelona, especially over the period since the 1992 Olympics. The height of this recent euphoria culminated with the celebrations and the many publications that marked Barcelona’s ‘Year of Gaudí’, the 150th anniversary of his birth in 2002.

For the great part, much of the work published on the architect can be regarded as ‘coffee table’ volumes, extended guide books offering a visual tour of his extant works. The American academic George Collins (1917-1993), was one of the first English speaking authorities on Gaudí’s work. Collins identified the challenge posed to further writing on the architect’s work
because ‘we are today largely dependent on what Rafols [Jose, (Rafols 1928)] and others had extracted and published previously. Little serious effort has been made to check their data through other sources, and very few new projects have come to light since’ (Collins, George R 1960, p. 130). Throughout the following three decades publishing scholarly articles on the work of Gaudí, Collins did not change his view that the fire that destroyed the architect’s archive of drawings and models in the Church burnings of July 1936 during the Spanish Civil War (1936-1939) served largely to sever the documentary link with Gaudí’s practice of the profession.

Aside from the built work, very little is attributable to Gaudí himself. Nearly all the quotations, oft repeated, are sourced from the publications to which Collins referred, for with few exceptions Gaudí did not publish his own thoughts or record the motivations behind his work. The exception, aside from the few drawings that remain, are to be found in the remnants of the model making activity that characterised his preferred working method during the final twelve years of his life. Alongside the models cast in plaster are the articulated mechanisms made with cord or string of variable length with which Gaudí demonstrated the principles of the ruled surface geometry that so captivated him. These demonstrative tools changed their shape with lengths of string so the variable parameters of the surfaces he animated into place could be visualised, thereby communicating his intentions. Today in the Technical Office of The Sagrada Familia I found similar tools are still used, not primarily to preserve any historical continuity, but because they are still an effective method by which to convey the principles of the architectural geometry employed.

It is this animation of surface and form that is captured with the parametric modelling, thus linking with a practice that was established almost a century ago.

The research carried out by the Technical Office of The Sagrada Familia contends that the method of plaster model making, which has its origins in mathematical instruction, was developed in Gaudi’s studio over a period of at least 30 years as the architect investigated techniques to describe the non-orthogonal forms of his architecture (Bonet i Armengol, J 2000). The great many models that were made during the final twelve years of his life, as well as his tendency to change and alter elements of his works even during construction, depict Gaudí as an architect of continual exploration. Individually, the plaster models might be thought of as static, but collectively, they perform as variants of a dialogue of ruled surfaces, it is the strict adherence to this type of geometry (particularly useful in construction), and to the graphic form finding methods of the period, that indicates a duality to the commonly attributed characteristics of deep idiosyncrasy and anti-rationalism.

**Background**

It has been said there were three beliefs that sustained Gaudí; the belief in architecture, the belief in a Christian God and the belief in Catalonia (Van Hensbergen 2001, p. 264). The first in the context of his work is understood, as well as the second, particularly with reference to
the liturgical narrative woven into the fabric of a church such as The Sagrada Familia. The third, a belief in one’s homeland, in the struggle of a region for its identity expressed as it is through language and traditions and, at the same time, often in opposition to the clergy, can be somewhat enigmatic when viewed from the outside. However, an understanding of Gaudí is not separable from his context.

Catalonia is situated in the north-east corner of Spain where, for the most part, surrounded by mountain ranges, it looks to France and the Mediterranean. Often throughout its history, Madrid has sought to assert its rule over the region, most recently under General Franco. During that period the Catalan culture was forced underground as Spanish political, cultural, educational and linguistic imperialism was enforced. The Catalan language, not for the first time, was banned. This regionalism, with its nationalist tendencies, has a violent history that reached well into the 20th century, as does the cultural nationalism of the Basque region of Spain even now.

Founded by the Romans, under the protection of Emperor Julius Caesar, Barcelona was first a colony called Barcino. That Roman colony is now the Gothic quarter found in the heart of the city. In medieval times the city expanded and became the centre of a commercial and cultural empire. Eventually the medieval city walls were demolished as the 19th century industrial city grew out to encompass the surrounding villages, with a grid of bevelled city blocks designed by the engineer Ildefons Cerdá, contemporaneously with Hausmann’s Paris. Hausmann carved through a city and Cerdá enlarged one: however, in common they both envisaged cities filled with perimeter buildings of a standardised height (Hughes 1992).

It was into this expanding wealthy region that Antoni Gaudí was born. At the time of his birth in the mid 19th century there was a renaissance of Catalan arts and crafts; newspapers had even begun to be published in Catalan, and in 1888 Barcelona hosted the International Exhibition. Gaudí, as a young architect establishing a practice, benefited at the time from an abundance of wealthy patrons, his being mostly textile manufacturers. Of these, Eusebi Güell is the most important, but also Josep Batlló and Pedro Milà both played formative roles in the development of Gaudi’s mature architecture (Martinell 1975).

**Works referred to in the research**

My research necessarily spans the entire length of Gaudi’s career without covering the full gamut of his work. This is partly because his tenure at The Sagrada Familia lasted almost 43 years, itself traversing the architect’s life. Difficult as it is to comprehend the length of construction within one person’s career, it is to be noted that during his lifetime Gaudí did not realise the ruled surface geometry proposed for The Sagrada Familia at full scale. In fact, it is only in the unfinished project generally considered by scholars such as Burry and Tomlow (1989) the precursor for Gaudi’s final forms – the church of the Colònia Güell – that ruled surfaces, in a similar manner as those intended for The Sagrada Familia, were constructed (Fig 3.04).
In many ways the Colònia Güell was a more radical proposition than The Sagrada Familia. It was asymmetrical, negotiated an undulating site and its form was found almost entirely through an optimal method of search using a three-dimensional model. This project, as well as the architect’s final secular commissions for residences such as the Casa Batlló and Casa Milà, catalogue Gaudí’s attempts to both construct and control a freer flowing geometry. Plaster models were employed on both the Casa Batlló and Casa Milà to describe complex surfaces which were entirely free-form in both cases (Collins, George R. 1963). These surfaces were supported upon structural parabolic curves, a form Gaudí had used since his earliest projects, and often found below the surface (Fig 3.05).

The plaster models of The Sagrada Familia can be viewed as the apotheosis of the pursuit to control form and a determination to wrest it into the third-dimension. A thread is drawn here between methods of three-dimensional representation to express difficult form, where
complex but controllable surfaces can be defined by geometrically using straight lines, but which also engenders the continuation of the use of structural parabolic curves – found in the cross-sections of these surfaces.

**A new church**

It is on the eastern edge of Cerdá’s bevelled blocks, known as the Eixample, (or Enlargement), that The Sagrada Familia church is located. Its full name: El Temple Expiatori de la Sagrada Familia (Expiatory Temple of the Holy Family) is a church dedicated to the Holy Family. It was conceived by the Association of the Devotees of Saint Joseph, founded by Josep Maria Bocobella, the proprietor of a religious bookshop in Barcelona. Bocobella envisaged a church similar to that of the Shrine of Our Lady of Loreto, which he had visited in Italy. Venerated within the basilica at Loreto, is a house believed in Catholicism to be the house of the Holy Family, transported from Nazareth by angels at the end of the 13th century after the failure of the last crusade.

So too The Sagrada Familia, always intended to be loaded with liturgical symbolism. Construction began on 19 March 1882 – St Joseph’s Day, with the first mass celebrated in the crypt exactly three years later. Gaudí was not the first architect for the church. It was the diocesan architect Francesco de Villar who planned a rather modest neo-Gothic church for the site, and although Villar’s tenure was short – Gaudí had taken over by the end of 1883 – the work undertaken during that initial period has dictated the layout and siting of the church.

The building of the church was a private enterprise, to be funded entirely through donation. Sporadic bursts of construction early on were financed with bequests, but in leaner times construction activity ground to a halt. During these periods, Gaudí, who was well known enough to the inhabitants of the area that they avoided crossing the road lest he should ask for contributions, would instead pursue the modelling of the church in plaster first at a scale of 1:25 and then at 1:10. These model investigations were both for new elements as well as the revision of earlier work. This process of re-working from early schemes through to construction was a constant during Gaudí’s professional career and his working methods evolved to suit the practice.

I found it of interest to discover The Sagrada Familia is not a parish church, nor yet a cathedral. Its significance, which has not been without religious and political intrigue at times, is probably closer to the more important churches, known as minor basilicas. Gaudí’s free reign with the design is attributed to the patronage of Bocabella who is credited with stirring Gaudí’s spirituality, a project it has been suggested the founder took on as personal challenge (Martinell 1975, p. 51). Bocabella, as a bookseller, also provided Gaudí with material to develop his religious symbolism and which he later potently mixed with Catalan nationalism.

Although control of the Association of the Devotees of Saint Joseph passed upon the death of Josep Maria Bocobella first to his son and then to his wife, in 1895 it was assumed by the Bishop of Barcelona. Gaudí continued to construct in his own manner a church which
appeared to be outgrowing the lives of those who had conceived it and their progenitors. It is probably a credit to his own assertive personality and the delicate politics played by those around him. His own proposals for the church began also in the neo-Gothic style but were distinguished by a dramatic increase in height.

By the time of Gaudí’s death in 1926, he had lived to see the completion of only one of the bell towers, the most southern, dedicated to St. Barnabas. The Sagrada Família had encompassed almost his entire professional career. He started at the age of 31, only having graduated five years previously in 1878, and worked continuously on the church until his death – a span of over 40 years – the last twelve of which were solely dedicated to the work.

Continuing construction

Those who continued the construction of The Sagrada Familia after Gaudí’s death can be divided into two principle categories: Gaudí’s senior assistants and his admirers. Of the admirers, some had a great degree of contact with him and also assisted periodically. It is the publications of these admirers, particularly the architects, Josep Rafols (1928), Cesar Martinell (1975), Puig Boada (1981) and Juan Bergos (1954), to whom the quotations and sentiments ascribed to Gaudí are attributed. Because Gaudí did not actively publish his work, apart from some early notes on ornamentation, it has always been others who recorded and published notes from the talks he gave and the personal conversations they had with him. Although enlightening, in their many subsequent publishings they are often not qualified and are used sparingly in this study.

Of Gaudí’s assistants, it was the architects Domenec Sugranyes and Francesc Quintana who carried on the construction of the church immediately after his death. Together they oversaw the completion of the pinnacles atop the three remaining Nativity Façade towers, which were finished by 1930. Between 1930 and 1935, the Nativity Façade gables continued to be adorned with works Gaudí had begun, including the crowning cypress tree and the statuary of the tower’s apostles.

The church and school burnings at the beginning of the Spanish Civil War in 1936, to which The Sagrada Familia was subjected, led to the smashing of the contents of the workshop that housed the models of the work. Sugranyes died during the Civil War, and it was not until 1944 that the construction committee was revived by Quintana and work began to reconstruct and conserve the fragments left of the plaster models. The architects, Isidre Puig Boada and Lluis Bonet Gari, both admirers of Gaudí – Puig Boada wrote the first book on The Sagrada Familia (1929) – then began preparing for the construction of the western transept in 1953. This is the Passion Façade, its authority vested in a sole surviving photograph of a drawing for the elevation (Bonet i Armengol 2000). This work is still underway.

Francesc Cardoner became the director of construction between 1981 and 1985, until the present director Jordi Bonet Armengol (Bonet Gari’s son) took over. Work now progresses alongside the conservation and reconstruction of the original plaster models, of which there
are over 4000 fragments identified, less than half the total in the archive.

**From Drawing to modelling: the evolution of Gaudí’s three-dimensional process**

There are many threads that might be drawn through the work of Antoni Gaudí; be they the perceptible influences of style (neo-Gothic, art nouveau or Modernista – the Catalan version of art nouveau), the politics of the time or even of architectural patronage. My research is interested in the development of technique, identifying a path that leads to a parametric model embodying both the plaster models of a restricted set of surfaces and possibilities of variation.

This process is characterised by the increasing three-dimensionality of Gaudí’s work during his lifetime and the techniques he engendered to promulgate three-dimensional definition, of which the Corbertes model is resultant. The process artefacts, the plaster models of ruled surfaces Gaudí left, while extant, are the least known of his works; somewhat paradoxical when one considers the church is his most well known work. How or whether they were translated to construction drawings is not known. It is not possible to undertake a scholarly comparison between the original technical drawings of The Sagrada Familia and the plaster models, partly as the majority of what was modelled was never built, but also because of the destruction of the technical drawings.

The first major survey of Gaudí’s surviving drawings was undertaken by Collins and Bassegoda during the 1970s (Collins, George R & Bassegoda Nonell 1983). They catalogued an inventory of about 200 drawings, and of those, drawings that could be classed as working or drawings for construction constitute a minority of the collection.

Gaudí’s drawings exhibit several characteristics. They are competent, varied in composition and technique, discounting any suggestion his later preference for modelling was a retraction from the two-dimensional medium through any personal difficulty he experienced. Gaudí did not necessarily build what had been drawn. Of the preserved drawings, some were from municipal archives, the drawings Gaudí submitted for official approval. Comparison with the completed buildings show he must not have felt compelled to adhere to what was shown. Collins (1977, p. 13) suggests that often this might not have been problematic as the authorities’ interest would have been centred on adherence with amenity and ordinance, but there are records that reveal this was not always the case (Van Hensbergen 2001, p. 174).

To describe the process in Gaudí’s studio as it related to drawings: it would often be his assistants who would draft the outline of a drawing, whereupon Gaudí would then sketch proposals over the top. In this way, the attribution of works has been made more difficult. He continued these methods in a series of innovative media; the watercolour renderings over photographs of the structurally optimal model for the Colònia Güell church being the most well known – a form of exploration subsequent to a search. Contemporaneously, he also did this for the Passion Façade of The Sagrada Familia, sketching proposals over a graphic static drawing he had made to analyse the structure (Collins 1977).
Even at the beginning of his career Gaudi did not feel compelled to furnish a project with technical drawings. Construction of the Casa Vicens (one of Gaudi’s earliest works, begun in 1878), for a tile manufacturer, is recorded as having been directed on site – without working drawings – but rather adhering to a specific tile module (Collins, George R 1960, p. 12).

Over 30 years later at the Colònia Güell church a similar relationship continued. ‘The long period of construction during which only a few bricklayers were working under the close supervision of the architects seems to indicate the difficulty presented by the construction. When Gaudi fell ill for several months in 1911 work came to a standstill until he had recovered his health’ (Tomlow 1989, p. 161).

Collins attempted to reconstruct the role of drawing at The Sagrada Familia, but limited his references to the work concerning the sculpture and statuary. Martinell suggested the preference for the drawing of the Façade tower’s pinnacles, the last element constructed before Gaudi’s death, was more a pragmatic decision to avoid Gaudi, in his later years, climbing the stairs to the top of the towers (Evans 1995, p. 334). In any case, these drawings seem to have been undertaken at a large scale, possibly full size, laid on the floor and frequently patched as additions or corrections were made.

It is possible to surmise that where a form was required to be wrested from a plane, Gaudí was not inhibited by the restraint of a drawing, either as provenance or as executor. Unlike a drawing studio, the workshop at The Sagrada Familia was filled with technicians and sculptors for whom drawings were not a prerequisite for communication. The methods concurred with those in his workshop and Gaudi developed to suit them.

Ruled surfaces

The restricted palette of surfaces Gaudi used to compose his final forms are known as ruled surfaces. They are the plane, the helicoid, the hyperbolic paraboloid, the hyperboloid of a revolution of one sheet, and the right conoid, of which all but the conoid are ruled in two directions, known as doubly ruled surfaces. In the context of Gaudi’s work they are sometimes referred to as Gaudinian surfaces (Rafols 1928). The effect is that curved surfaces, can be constructed from straight lines. It is the hyperbolic paraboloid that is of special interest for this study. 4

![Figure 3.06 The hyperbolic paraboloid shown with lines of ruling.](image)

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4 The hyperbolic paraboloid is of special interest for this study as it is a ruled surface that can be constructed from straight lines.
The plane, although two-dimensional, qualifies as a doubly ruled surface. By lifting one corner of a plane, the resulting non-planarity affects the hyperbolic paraboloid. In an effort to visualise this plasticity, the following figure is shown, from an animation I made to demonstrate the movement of these surfaces (the plane to a hyperbolic paraboloid) for a column at The Sagrada Familia.

![Figure 3.07 Animating a plane to a hyperbolic paraboloid. The surface adheres to being double-ruled as it is stretched to form part of a column.](image)

Gaudí’s use of helicoidal form can be traced through his chimney pots, and his experience with this particular geometry was extensive; including rotating two helicoids in opposite directions as for the central nave columns in The Sagrada Familia. An architectural education at the end of the 19th century included forays into physics, mechanics and mathematics as well as geometry and would have introduced Gaudí to the basic geometrical curves: the circle, the ellipse, the parabola and the hyperbola. These curves, known as conics, are derived from the sections of a cone and their definition dates to the ancient Greeks. In the third dimension, their surface equivalence is found by rotating the curves about their respective axes; so a revolved circle produces a sphere, an ellipse, an ellipsoid and so forth.

The course in descriptive geometry undertaken by Gaudí covered ruled surfaces, those surfaces yielded through the sweeping movement of a line through space (Alsina & Gomes-Serrano 2002). Descriptive geometry, as it was taught to students in the late 19th century was the generalised method founded by Gaspard Monge at the École Polytechnique in Paris for describing three dimensions in two. Amongst his other generalisations was the practice of stereotomy (making templates for the cutting of stone) and skiagraphy (the technique to embolden an object through the application of shadow). Monge, as a mathematician, presented geometry as an equivalence to the algebraic mathematical concepts made possible by René Descartes’ cartesian co-ordinate system (Evans 1989).

Modern architectural drawing is regarded as a descendent of Monge’s methods of descriptive geometry cf. Bois (1983) and Evans (1995). As an activity largely independent of its mathematical origins its influence is closer to that filtered by the École Polytechnique’s
professor of architecture, J.N.L. Durand. Evans (1995, pp. 324-7) argues that because of Durand’s ‘reduction to planning grids and orthographic projections’, it is in fact engineering drawing, and particularly mechanical engineering, that are the disciplinary inheritors of Monge’s principles of descriptive geometry. These techniques include methods of describing warped forms, particularly for industry, such as the ruled surfaces of ship’s hulls. It is of interest then that in architecture when these surfaces were ‘rediscovered’ during the mid-20th century, they were called the ‘new shapes of the fifties’ (Boyd 1965, p. 98) and are still considered ‘special structures’ (Bradshaw et al. 2000).

**Mathematical influences**

Gaspard Monge was also one of the originators of mathematical surface modelling. Mathematicians during the 19th century were investigating increasingly ambitious concepts and models, used primarily as visual aids for instruction, and which were constructed from cardboard, string, plaster or wood. These models began with basic polyhedra – the platonic solids – and included ruled surfaces through to non-euclidean geometry, such as the single sided Klein bottle.

Figure 3.08 Mathematical surfaces wire and solid (University of Arizona Department of Mathematics http://math.arizona.edu/~models/ accessed 9 September 2004).

Primarily confined to the departments of mathematics in universities, just as their usefulness dissipated in the face of the general move towards the dominance of instruction in analytical algebra during the early part of the 20th century, these models inspired artists, particularly the abstract spatial investigations of the constructivists such as Antoine Pevsner (Fig 3.09). Infusing meaning through art and geometry would have accorded with Spanish mathematicians of Gaudí’s time, who affiliated mathematical beauty to both nature and a fervent religious symbolism (Collins, George R. 1963, p. 70). Although there is reference to Gaudí not being enamoured with algebra or analytical geometry, there would seem to be little use in passing on to his assistants the equations of the surfaces he intended (Alsina & Gomes-Serrano 2002).
Copyright works removed

Figure 3.09 Pevsner, Vision Spectral sculpture.

Today it is computer graphics that have again reintroduced visualisation to mathematical concepts, from the interest in fractal geometry and its relation to nature through Mandelbrot sets, to animated projections that give a sense of higher dimensions, such as the hypercube – a cube of the fourth dimension.

From two dimensions to three

After 1900, a new fluidity has been noted in Gaudí’s drawings and works, both for buildings and furniture (Collins, George R 1977, p. 17). This in turn led to a plasticity of surface which has a correlation with the curves of the conic sections and their resultant surfaces, but it is not immediate. Gaudi’s progression from a planarity of surface to three-dimensionality is first in free-form and then later with mathematical rigor. Although effort has been expended by scholars to identify the first use of ruled surfaces in Gaudí’s work, another trajectory, with the assumption of his familiarity with them, is to reason that their application during a lifetime’s work might not be of a linear progression. In fact, the circumstances that brought about the use of ruled surfaces at The Sagrada Família may not have been apparent when Gaudi first used such a surface.

The parabolic conic section is commonly found in engineering work. It provides an efficient form capable of uniformly shedding a load while containing outward thrust. The most efficient shape in this regard is the catenary curve which is very close to, and was thought up until the 17th century to be, parabolic. A catenary curve is the natural funicular found simply by hanging a chain supported only at its ends. It is equally simple to understand how the forces are resolved when considering that the relationships of the links (if it is a chain) are tangential to one another. The concept incurs a difficulty in theory as the formula for a catenary is inexplicit, and so for that reason parabolas have historically been substituted for the ‘ease of use’ reason in effectuation.

Gaudí was clearly aware of this, most famously with the funicular (catenary) model for the Colònia Güell church, built using hyperbolic paraboloids (parabolic sections), and earlier when parabolic arches he employed were superimposed in the structure with a catenary curve, the difference being made with a section of laminated brick or Catalan tiling (Fig 3.10).
Chapter Three

Figure 3.10 The superimposition of a catenary and parabola at Casa Vicens (Collins, GR 1963, ‘Antonio Gaudí: Structure and Form’).

One of the first uses of the parabola in Gaudí’s work was in the form of an efficient arch in the workshop for a textile cooperative in Mataro, outside Barcelona (1878-82). It is interesting to note though that the continuous curve of the structure did not impact on the workshop’s external form. That took the form of a gable roof on vertical walls (Fig 3.11).

Figure 3.11 Parabolic structure within the workshop for the Mataro collective (Credit Collins, G 1960, Antonio Gaudí).

The parabolic solution returned in the stables for the Güell Estate (1887), where the parabolic arches (in brick this time) were extruded as barrel vaults with glazed ends allowing the interior to be bathed in high level light, again without making an impression on the exterior. Later these forms were expressed in the surface as well as the structure. Parabolas form an alternating brick relief in the upper floor of the austere Convent school of Saint Teresa (1888-90), and begin to dominate the form at the Bodegas Güell (1895-1901), where the central building’s profile is a parabolic extrusion (Fig 3.12).
Gaudi’s first foray into a three-dimensional surface on a building – an example of the kind of ‘fluidity’ in the work that began after 1900 – is with the roof of the Casa Batlló (1904-1906). This project was a refurbishment of an existing building, with the most dramatic work being the over-cladding of the façade to provide balconies to the existing openings. Shapes recalling bone structures have attracted anthropomorphic labels to this building, and the roof addition, which contains an attic, has been described as a fish (from the scale-like tiling), a dinosaur (from the spiky roof ridge), and also dragon-like. The latter invokes homage to St. George, the Catalan patron saint, with the adjoining tower serving as his lance – embedded in the dragon. This reference, as well as the Casa Batlló’s location – it is found in the ‘block of discord’ – its neighbours are all various attempts of the Catalan art nouveau or Modernista has served to link Gaudi with that movement (Van Hensbergen 2001).

Collins (1977) documented the development of roof of the Casa Batlló first as a free form surface, supported by a series of undulating parabolic arches and after which the surfaces were designed with a plaster model – no longer in existence. By contrast, the curved surfaces of the roof were represented on the official drawings with only the barest outlines (Fig 3.13). Gaudi’s design methods are exposed in a sketch which is an overlay of a drawing provided by an assistant, that by comparison with the official drawings show the façade, particularly the upper section and the roof, in the process of substantial alteration – exposing that trait of Gaudi’s, usually continued through construction.
I believe that the Casa Milà (1906-1910) is probably the most well known of Gaudí’s secular commissions. It is a building also modelled in plaster, and once again the roof undulates over parabolic arches. It is the façade though, where the stone is hung from a steel frame, that is of real interest in following the continuation of Gaudí’s experiments in three-dimensional freeform. The project soared in cost, almost bankrupting the builder and requiring the architect to sue for the final fee – a process that was protracted over several years after the building was completed. It was the façade that was largely to blame, with each piece of stone being adjusted and lifted into place four times on average in order to match its neighbours, and although it has been called an impressive example of stereotomy it rather fails the test of belonging to the science of stonecutting.7

During the period that encompasses the design and construction of these free-flowing surfaces (the roof of Casa Batlló and the façade of the Casa Milà), the church of the Colònia Güell had begun construction (at the end of 1908). Built with a funicular model that was located for reference in a shed on site, the slow progress and the requirement for constant supervision must have caused Gaudí to consider how such surfaces were to be built. At this time, hyperbolic paraboloid surfaces were being introduced to Colònia Güell, but were being built from brick.

Successive drawings through The Sagrada Família show a church that, between 1908 and 1915, is clearly of neo-Gothic underpinnings with parabolic influences. This is most obvious as the arches develop surfaces of hyperbolic paraboloids and helicoids. Gaudí’s enthusiasm for these surfaces, particularly the hyperbolic paraboloid, was because they were indefinitely variable, but the principles remained – through their ruling lines. In fact, he parameterised models describing a hyperbolic paraboloid made with red thread that he would hold above a table as the sun created shadows of the ruled lines (Alsina & Gomes-Serrano 2002).

The brick hyperbolic paraboloids at the Colònia Güell were the furthest this surface investigation progressed at full scale. The Casa Milà was Gaudí’s final secular commission and all further work at The Sagrada Família was carried out in plaster form – albeit in a highly sophisticated manner and to a detailed scale up to 1:10.

3.2 Complicated forms

The Sagrada Família fits within the gamut of complicated three-dimensional forms that are challenging to document and construct using standard orthogonal representation. The buildings of Frank Gehry are contemporary examples of the negotiation of the buildability of a project, just as the Sydney Opera House was during the mid-20th century. Taffs (2006) describes the models developed to analyse the Sydney Opera House, including those of perspex and wood, as well as computational, and the architectural historian Robin Evans (1995) cited the example of the difficulty in realising Hans Scharoun’s Berlin Philharmonie (1956 to 1963) as the project was translated from sketches and models to working drawings.

Tom Heath describes the affordance offered when a design is unencumbered by its social
constraints.

‘Inevitably, the greatest volume of design work, in architecture as in other fields, concerns itself with products that are near to the commercial end of the scale. As one moves away from this well defined, near routine activity towards the experimental, the exploratory and the symbolic, the demand for innovation increases, and with the opportunity for creativity.’ (Heath 1993, p. 13)

Heath refers to the house typology as the most obvious example of the domain for architectural invention, but the use of computation has increased the scope for architects to work on vastly larger and more complex projects. Pérez Gómez and Pelletier referred in 1997 to the already (then) apparent opportunities to detail complex forms and ‘facilitate the construction of complex buildings with increasingly smaller tolerances’ as examples of the promise of computing in architecture (1997, p. 377).

On The Sagrada Família and what makes it a good case study

Gaudi’s legacy covers a broad spectrum. The Sagrada Família spans his built works to his final twelve years in which he worked in relative obscurity. I have looked at the developments of the final forms for The Sagrada Família as a legacy of a rare combination of longevity, technological achievement and synthesis; they have effectively leapfrogged most of the computational development in architecture during the 20th century. Rather, in the intervening period, Gaudi’s place in history has been fought over in terms of classification and influence. To briefly outline the development of Gaudi’s reputation, there are three major periods in that can be discerned. First are the years of decline. They can be dated from his last secular commission, the Casa Milà, in the early years of the 20th century. Although construction progress of The Sagrada Família’s Nativity Façade kept Gaudí in the public’s mind, a younger generation of architects had moved on stylistically from the Modernista style of Gaudi’s contemporaries. This period extends to the centenary of Gaudí’s birth in 1952, during which time, by way of example, Nikolaus Pevsner did not include him in his Pioneers of the Modern Movement in 1936 (Fuller 1988, p. 120).

The use of graphical methods of engineering also declined, all but subsumed by analytic methods of algebraic and calculus, which in turn saw the end of mathematical models in schools and universities. Professional bodies attempted to standardise drawing conventions. A year after Gaudi death in 1927 the British Standard for engineering drawing was the first legislated standard for drawing (Hambly 1988, p. 17).

The second period of his reputation began in the 1950s. The Architectural Review published a retrospective, initiated with an exhibition, to celebrate the centenary of Gaudí’s birth. At this time Quintana, Puig Boada and Bonet Gari, who had been slowly piecing the models together, reconvened the construction committee and a conference in 1959 considered the way forward, initiating the forum which took the responsibility for deciding how to (or whether to) complete The Sagrada Família.
Although his intentions are not recorded, Gaudí was rather shrewd in this regard. By building a section of the church vertically (the Nativity Façade) to its completion, he has succeeded in stamping his signature upon the project. By contrast, John James’ research found evidence of successive construction campaigns to build the cathedral at Chartres in horizontal layers of the entire building rather than in sections (James 1982).

The vehemence with which opinion was held about Gaudí can be witnessed in the exchanges between Reyner Banham and Nikolaus Pevsner, the latter who had moved somewhat to revise his position by suggesting the roof of the chapel at Ronchamp might be considered to be of Gaudinian progeny.

Banham’s rejoinder that ‘Le Corbusier has used such a “ruled surface” once – in the Philips Pavilion – but in an utterly different sense and intention’ and ‘Neither Engineering or Gaudí really explains, say, the roof at Ronchamp’, reaffirms the position that Gaudí (even though a ‘contributor to a provincial branch...of International Art Nouveua’) remained ‘a Nineteenth Century Gothic Revivalist’ (Banham 1961, pp. 82-8).

The proponents of the argument seem to be completely unaware of the technical drawings for the roof of Ronchamp, describing the roof as a right conoid flanked on either side by hyperbolic paraboloids. This was the result of a process which involved moving from sketches to modelling in plaster and then wire.8

Le Corbusier, who had visited Barcelona in 1928, sketched the roof of the provincial school at The Sagrada Família – a double conoid (Evans 1995, 304).

3.3 Examples from other industries

The research work at The Sagrada Família originally used the parametric software product CADDS-5 by Computervision, and more recently CATIA, (Computer-graphics Aided Three-Dimensional Interactive Application) developed by the French aerospace company Dassault. Software originally intended for uses other than architecture is not unencumbered with the methodological assumptions of its own domain and these have to be factored in terms of the transfer of technology. In this research I have considered parametric modelling as a technology, using Volti’s (2001) definition by which to understand its broader implications for change as ‘a system based on the application of knowledge, manifested in physical objects and organisational forms, for the attainment of specific goals’ (Volti 2001, p. 6).

The use of parametric modelling is well advanced in manufacturing industry where products are routinely computer-aided designed and manufactured10. Developing forward-looking drawing and modelling software requires significant research and development and there is a history of tools and systems that have become significant software products evolving from their original use for specific ‘in-house’ applications within manufacturing organisations. In this section I also refer to experience gathered outside architecture during the research, including a site visit to Ford Australia, attending the International Manufacturing Leaders Forum hosted by the Centre for Advanced Manufacturing Research at the University of South
Australia, and from the opportunity presented when I was invited to present my research during Australian National Manufacturing Week in 2003.

Bézier curves are an example of an application finding the broadest of audiences, an example I recall from an obituary I read for Pierre Bézier (1910-1999). The smooth free-form curves that can be manipulated parametrically using control points found in most computer based illustration, drawing and modelling software, are named after Bézier. A mathematician and engineer who worked for the automobile manufacturer Renault, Bézier developed them for use with computer graphics. In application they were used to help design vehicle surfaces when greater accuracy was required for describing curves which had been previously drawn with french curve templates.

In some cases, a chronological schism can be detected. For example, the aforementioned Dassault began designing aeroplanes with three-dimensional computer models in 1975\textsuperscript{11}. Their methodology in 1975 was to first consider the minimum to be modelled in three dimensions and then slice the model to provide two dimensional drawings for drafting over. A matter of resources and efficiency, this technique was similar to the position I described while working on the Federation Square project 25 years later.

Early in the research, to ascertain how parametric design was used in manufacturing, I visited the Ford Motor Company plant in Geelong, Australia. Ford has manufactured vehicles in Australia since 1960, although it has been assembling cars here from early in the 20th century. At the time of the visit Ford manufactured one vehicle in Australia, the Falcon. This automobile is produced in various guises, from utility and family car to luxury saloon.

It was an optimal time to visit. The current Falcon was the first design that was entirely model based. The company had just finished integrating the local operations with the global Ford network. The production manager initially described the transition from the previous model, which had been designed and built with a strategy of 70 per cent drawings and 30 per cent modelling, as a simple argument of economics. Had it not moved to integrate with the way the broader company operated, Ford Australia risked being excluded from international Ford research and development, and thus reduced from a manufacturer to a reseller.

Ford was not alone in the move to a modelling environment. It operates in a cut-throat business and automotive companies, and importantly their thousands of suppliers, have a long history of innovation or oblivion. Womack et al (Womack, Jones & Roos 1991) describe how the Japanese car makers won much of the American market from domestic manufacturers by introducing new methods, such as carrying lower inventories of stock which allowed them to make improvements during the production cycle.

Ford was an excellent example of the control an Original Equipment Manufacturer (OEM) exerts in a vertically integrated industry. All the components for its vehicles, whether produced in-house or by an external supplier, were to be produced from the model information, in the same software environment. No drawings were to be exchanged and a huge investment in resources and training had been required to receive and work with three-
dimensional information at all levels of assembly.

By way of contrast to parametric models for Gaudi’s surfaces at The Sagrada Familia, the parametric models Ford used at the time were quite simple. An example presented was of a bracket with a slot that moved parametrically along the length of the bracket to suit the housing of the vehicle’s radiator. They were simple geometric models within a sophisticated system. At the end of each working day the design teams at Ford Australia save their work which is then uploaded to a central repository in Detroit.

The significance of this centralised storage of information registers on a number of levels. Firstly, the company can view all the components for each automobile as belonging to a large parts bin. This means the aforementioned radiator designed by someone in Ford Australia could be shared with the development of Jaguar in the UK. Engineers might work on the same part the next day and then, when the Australian engineer arrived at work the next day, the model could be downloaded with notes for consideration. The parametric model could then be varied to suit both vehicles.

Secondly, the model method provided a greater degree of co-ordination. Automobiles are designed by teams of engineers who specialise on different parts of the car. The production manager at Ford explained the confused meetings that occurred when teams would meet with paper drawings and try to understand relationships between the parts of evermore complex vehicles. The boundaries between disciplines and teams are easily identified in vehicle production as most warranty issues have been observed to arise at the interfaces between different areas of work (Robison 2005).

Karl Sabbagh’s (1996) account of the construction of the Boeing 777 reveals similar motivations for moving to model form to represent the aeroplane, described as ‘4 million parts all moving in close formation’ (Sabbagh 1996, p. 29). ‘Traditionally new planes had been designed in two dimensions: drawings on paper had been used as a basis for the manufacturing process. But to design a plane entirely this way, with over 100,000 different three-dimensional parts would have led to unpleasant discoveries at the assembly stage.’ (Sabbagh 1996, p. 50).

Co-ordination had previously occurred in staged full sized mock-ups, where the components for aeroplanes were brought together. Using a fully co-ordinated parametric model, the first mock-up for the 777 by contrast was also the first plane to fly.

Boeing is not only a user of parametric modelling and relational databases, it is also a developer. Boeing helped develop CATIA for Dassault. In turn, Dassault is an aerospace manufacturer that first designed with digital models in 1975.

Industrialisation has long provided a source of speculative attraction to architecture. In one of the latest exhortations to the architectural profession to once again consider production processes for building, Keiran and Timberlake expose – almost as an aside – the broader web of disincentive that pervades the transfer of technology from manufacturing to building.
Citing their own attempts to introduce offsite assembly fabrication, the following terms are used: ‘different contractors... unable to coordinate...offsite; contractual, labour agreements’ (Kieran & Timberlake 2004).

The opposition Keiran and Timberlake have faced as they pursue what I believe are laudable aims, arises from the simple fact that manufacturing is highly structured and OEM’s exert almost absolute control over the entire production process. OEM’s could be of considerable interest to architecture both as a source of technology transfer and in their business evolution from industrial to organisation entities. This especially relates to the role the computer has played in the transition, particularly through product design and description. Further research in this area, which is beyond the scope of my own work, could focus on the changing role of the client in relation to the evolution of technology.

### 3.4 Conclusion

In this chapter I have given an overview of the career and oeuvre of the architect Antoni Gaudí and traced his innovative approaches to design and modelling. I have also introduced The Sagrada Familia church in Barcelona as the major case study for the research, and as a special case in which the use of parametric design in architecture has developed as an innovation well matched to Gaudí’s methods. The Sagrada Familia church is a non-standard building and such buildings offer those working, designing and researching in the construction sector opportunities to test new methods of working and communicating to deliver projects, and where both representation and notational structures can be challenged.

Parametric software has its history in the manufacturing industry and I have given examples of its use to help the reader understand the context in which technology transfer of parametric design is occurring.

I found a nice circular reference between complicated forms in architecture and industrial production in the work of Tom Heath (1993). While Sabbagh (1996) described the Boeing 777 as a site for the implementation of new technologies, Heath referred to an earlier Boeing project, the 707, as an example of improvement through incremental change – the 707 gained twice the range and payload of its predecessor and that had implications for the system of air travel. Major change, Heath argued is only possible at the periphery, and this is the opportunity offered by a case study such as The Sagrada Família church in Barcelona.
Endnotes

1 See appendix for details of the ARC SPIRT grant.

2 The term ‘assistant’ is most often applied to those architects with whom Gaudí worked and collaborated. It would be a misnomer to consider these architects as employees as often they had significant practices of their own running in parallel. There is confusion over the attribution of authorship of some projects. The Güell cellars (Bodegas Güell 1895-1901), for example, have often been assigned to Francesc Berenguer, and it seems likely he carried out most of the work. Collins claims Gaudí would also sign drawings as ‘favourites’ to other architects (Collins, GR 1977, The drawings of Antonio Gaudí, The Drawing Center, New York, N.Y.), and this kindness serves to partly explain the ‘drawing over’ process where architects would draft the underlying proposal with Gaudí sketching over the top.

3 Van Hensbergen details the legal problems that beset the construction of the Casa Milà ‘Out of thirty-six months the Casa Milà had been legal for just four weeks’.

4 Gaudí predominantly used the hyperbolic paraboloid surface in three ways. Isolated, and therefore defined by four points, or in assemblies, either joined at their edges with adjacent surfaces, or located upon the internal ruling lines of another (parent) hyperbolic paraboloid surface.

5 Both Bassegoda and Collins, for example, identify the first time Gaudí used these surfaces.

6 ‘A vault with a parabolic or hyperbolic profile can provide a more generous concavity than does a semicircular one, so that if, for example, windows are to be set into the soffit they can be taller and admit more light.’ (Hersey, GL 2000, Architecture and geometry in the age of the Baroque, University of Chicago Press, Chicago. p.146-7).


8 Robin Evans quotes notes from Maisonnier (Le Corbusier’s assistant on Ronchamp) as to the modelling process undertaken for the realisation of the church (ibid. p.302).

10 The Australian Bureau of Statistics specify manufacturing industry in Division C of the Australian and New Zealand Standard Industrial Classification as relating ‘to the physical or chemical transformation of materials or components into new products, whether the work is performed by power-driven machines or by hand.’

11 As related by Dassault CEO Bernard Charles at the CATIA forum during Australian National Manufacturing Week in 2003.
Chapter Four Design of work

Introduction

Chapters Two and Three provided the background material for the study. Chapter Two introduced parametric design and discussed some of the considerations for its implementation in architecture. Chapter Three located the context of work in relation to difficult geometric forms, particularly with reference to the sponsoring major case study, at The Sagrada Familia church in Barcelona.

The aim of this chapter is to introduce the design of the research. This chapter includes the hypothesis of the work and a description of the several supporting case studies in their chronological order and why some of these case studies were eventually used for this research.

With reference to the background chapters, Section 4.1 describes how my research’s hypothesis is drawn. Section 4.2 examines some of the research methods used in architectural praxis, the notion of research and development in architecture. It discusses the case study research method and why it was chosen. The case studies used in the research are then presented in Section 4.3.

4.1 The hypothesis and research question

Chapters Two and Three, my background chapters, outline the technical component of my research within its context. Chapter Two details the development of parametric modelling within the paradigm of computing in architecture and Chapter Three sites the context of the research – complex forms that offer opportunities for exploring architectural praxis through their resistance to description by the architectural medium imposed upon them (Evans 1997).

I kept mulling over in my mind during the research a quote, referred to in Chapter Two, written by Rafael Sacks, Chuck Eastman and Ghang Lee: ‘The expertise regarding rules for parametric boundary conditions is not widely available and will become a growing area of research’ (Sacks, Eastman & Lee 2004, p. 293). This quote helped formulate my research question; what are some of the boundary conditions when designing and working with parametric models in architecture?

The core hypothesis of my research is that the parametric modelling of complex forms can reveal lessons for how architects can better understand the adoption of parametric design in architectural praxis more generally.

4.2 Design research

To test the hypothesis, the work at The Sagrada Familia is used to identify boundary conditions for the use of parametric design in architectural praxis with further project-based investigations undertaken as case studies.
In describing how this research was undertaken there are a few elements to first ‘unpack’. To introduce these elements I’ll call them, firstly, the notion of research through design, secondly, the location of the research as a site within its context in this case I’ll be referring to the ‘grey zone’, and thirdly, the mode of the research, how it was undertaken and what I brought to it. These are all elements that need to be declared and I have found they are not easily separable. Then I describe how I selected the case studies.

**Research through design**

In determining which method or methods to employ in design research. The research design for design research is not constrained by any one method (Downton 2003, p.17). For my research, inasmuch as each of the case studies is a ‘phenomenon specific to time and space’ (Johansson 2003), they were equally design projects in which a proposition was made and then tested. When researching through design, it was the results of each project through which further propositions could be made which in turn formed the criteria for establishing the next case.

My role was specific in two ways; the first was the role in which I operated. As a designer I was engaged with the process; parts of these projects are my specific design work, although the authorship of the building design in all of the projects is by others. For example, for one project, the Parametric Bridge, my work was informed by me as a designer and architect and the parametric model was designed and created by myself. Yet I would hold no claim over the work of the bridge as the architect. Rather my work as a designer was embedded in the research, which enlivened the bridge parametrically to many possibilities from the rules of the bridge’s architects.

The research also has an ‘inside’ and ‘outside’ aspect to it. As a registered architect, who has practiced professionally, I undertook the work as an informed researcher in the sense that I am no stranger to either architecture or construction and so I declare that in my research I am an ‘insider’ to the processes that unfold during design. While allowing me to research through designing, I recognise that such a role can also blind the researcher to artefacts in the process, such as work practices that surround design (Lawson et al. 2003).

There are two research techniques used in social science which have provided me with some insights and have helped to distinguish this way of researching as a designer ¹. The first is that of the ‘practitioner observer’, a role in which the purpose is to ‘develop an insider’s view of what is happening’ in social situations (Genzuk 2003). The ability to record work processes and activities that take place within offices is important to the practitioner observer. The second technique is that of the action researcher, whose work supports and guides social change in a situation in which the researcher is participating and in which the researcher may also be an insider – to improve the participants’ practices (Bowling 1997).

In that one could be more an observer than a practitioner or vice versa, Hughes (2000) has provided a scale of intervention to which he has termed corresponding research roles, the
‘observation-participation-action continuum’. Expanding on the degrees of intervention and their associated roles, at the low end of intervention the researcher role is limited to observation only, perhaps of a particular social structure – through the video taping a classroom for example. At the other end of the scale, where there is a high degree of intervention, Hughes has termed the research role ‘participant actor observer’ [my emphasis]. Hughes’ example of the latter role is ‘a child psychologist tries a new clinical intervention and observes outcomes’. It is this type of role that is closest to the way in which I undertook this research.

The way in which these projects were tested involved my research through design, with an insider’s knowledge, but they were located ‘outside’ the firms in which they originated. ‘Outside’ in this sense refers to being outside the systems for production of a project in practice. So the timescale for reflection of the case studies has an action present or zone of time in which the act of reflection can make a difference over the span of the entire research (Schön 1983). The case studies, with one notable exception, were therefore tests – either in parallel or in post mortem – of actual projects in firms. In taking the projects out of the firms, the intention was to mark them as research studies. Exposing the work to practitioners as research mediates risk one engages with in doing research – it is necessarily speculative and may not work in the environment of a firm. It also helped to define the relationship of the academy with that of practice as a laboratory into which projects could be interned for examination. This then informed the mode in which the research was undertaken.

**Operating in the grey zone**

I have been interested in this mode of enquiry, conducting research alongside practice, as a type of research and development function. In my research I found of interest Esa Laaksonen’s contribution to a volume entitled Research and Practice (2001) from a symposium held at the Architecture for the Alvar Aalto Academy and Helsinki University of Technology. Laaksonen referred to the Grey Zone (see Fig 4.01) as an expansion between a perceived border in architecture that separated what was considered research and practice. Laaksonen stated that ‘overcoming this borderline is regrettably rare’ (Laaksonen, Simons & Vartola 2001, p. 6).
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**Figure 4.01** ‘The operative cloud in architecture’.

I found the question becomes not so much how elements of practice are considered research, but rather how is research which partakes in or surrounds practice structured.

The methodology I applied in each case study was to bracket each in time, with starting and ending points, and also to present the work to peers, either in colloquiums or more formally at conferences. I also often wrote reports for the sponsoring organisations and I wrote papers to further extend and test the ideas that each case study embodied. Writing papers and presenting at conferences served a very useful function in extending the research, through the feedback I received.

Each output, of course has its own audience and I was struck by the difference between audiences, often immediately gauging the work within their own operative context. I concur with Manley, Marceau and Hampson’s observation within their survey of the output of research in the Australian construction context that ‘it might be considered that the industry is yet to become a demanding user of research outputs’ (Manley, Marceau & Hampson 2001, p. 19).

In most of the cases the research was done in parallel with the process as it happened “in practice”. In advance of introducing the case studies I note that this parallel working of research alongside practice was not a rule per se, but rather a caveat I drew about each research project. The caveat, or as I thought of it, the rules of engagement, were developed around a way to manage risk. That attitudes to risk are known to hamper innovation is well documented in many contexts particularly in construction (see large industry reports such as Department of Industry, Science and Resources 1999 and Rigby, Dewick & Bleda 2005) I offered no warranty that the results of any particular case study could be immediately adopted.
into practice. This was not necessary with the major case study at The Sagrada Familia as all research work undertaken by either RMIT University or the UPC is filtered through the Site Office. However, when an interesting project came along, I found it useful to declare that the research was by its nature speculative and ought to be considered not to fit within the usual construction processes.

Having a stance such as this meant the firms I was dealing with had to make alternative provisions and these proved to be very useful to benchmark my own work against. In one case, the Docklands Tubes, there was no alternative process because it simply would have been prohibitive to build in any other way and this case proved to be both rich and buildable! Anni Vartola, in her summary of the Helsinki seminar for *Architectural Research Quarterly*, stated that ‘The most fruitful way to understand the relationship between research and practice in architecture is to practice architecture at the highest level’ (Vartola 2000, p. 326).

In developing a way to operate in practice, I found particular value in the writings of the former head of Arup Research and Development, Steven Groák, particularly the concept of *Practitioner Researchers* he described with Krimgold (Groák & Krimgold 1989). The idea of Practitioner Researchers is that their modus operandi will transcend the project-based nature of architecture and uncover lessons for wider adoption within their particular firms.

### 4.3 Case study research in this project

This section gives a brief description of the studies the research used and why they were selected. The cases were selected purposefully (Johansson 2003). In the first instance, I was offered projects which came to the Spatial Information Architecture Laboratory at RMIT University, with the proviso that they should contribute to the broader research. I present the work chronologically, and graphically relate the research to output in Fig 4.03. I describe how the projects presented themselves and why they took certain trajectories.

I have used both Stake’s (Stake 2005) and Evans’ (Evans, D. & Gruba 2002) enunciations on case study research. Evans makes a neat division between *studies* and *case studies*, and this research, at the beginning, could have gone in either direction. Instead of the case study approach I favoured, a focussed study could have been constructed on The Sagrada Familia alone as a self-contained investigation into the use of parametric design in a particular, if somewhat special, project. In my research I selected and constructed case studies that would further test parametric design and broaden the research to learning lessons from the major case study, that of The Sagrada Familia church.

In positioning myself to be able to reflect upon how the work undertaken at The Sagrada Familia is translated into contemporary projects, the early intention had been to use a single case study for comparison. The Federation Square project in Melbourne was originally intended for this purpose and the necessary approvals to use it as a case study were gained. As discussed earlier, Federation Square had provided much personal motivation for the research and there was also an investment in personal experience that could have been drawn upon.
with the way it was built and the possible alternatives.

That other studies were selected from the pool of research undertaken at the Spatial Information Architecture Laboratory also charts where the tentacles of the research took the work. The project for the Selfridges Bridge is an exemplar of this. As the literature search for Gaudí and The Sagrada Familia began, one of the earliest books read was Robert Mark’s Experiments in Gothic structure (Mark 1982). Professor Mark had published a remarkable illustration from the Beaux Arts Professor Julien Guadet (1834-1908). Not only is there an uncanny similarity between their names – Guadet and Gaudí – but Julien Guadet had provided a project for a geometric variation to the Gothic church of St Ouen in Rouen. Guadet’s alternative was to rethink the gothic buttresses as parabolic arches (Fig 4.02). It was an alternative that resonated with Gaudí’s use of parabolic form at The Sagrada Familia.

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**Figure 4.02** Julien Guadet’s alternative for the church of St Ouen in Rouen.

Having pondered this, I wrote to Professor Mark in New York asking his thoughts on the extent of influence Guadet may have had on Gaudi and in fact what might have persuaded Guadet to pursue such a hypothesis. They were in fact contemporaries. Professor Mark kindly responded with an introduction to one of the enthusiasms of the time, graphical analysis, and, although this is not the appropriate section of the project to describe in detail, suffice to say
that both Guadet’s and Gaudí were using graphical analysis both ‘to solve structures not easily treated before its introduction’ (Mark - personal communication 2002) and to find forms, or form-finding as it is known – Guadet in two-dimensions and Gaudí in his special applications of three-dimensions.

Professor Mark suggested to me that finite element analysis, used for solving complex problems in engineering, could be considered the equivalent today of graphical analysis, and I found such analogies particularly useful for directing the research and selecting case studies.

For example, while researching Gaudí’s extant model on which the project was based, I became very interested in its genesis and in turn the large hanging model Gaudí used for the Colonia Güell church. One of the most interesting features was the model’s function, through which different disciplines could collaborate (engineers, architects and contractors used the Colonia Güell model).

At the time, in 2002, I was working on a case, the Parametric Bridge (I) for the consultancy firm Arup, and I proposed a second study to see if we could establish a contemporary digital version of Gaudí’s hanging model. So the case for the digital hanging model was developed from an existing case, but shaped and formed around the developing questions of my research at the time: can we share parametric models between disciplines?

So, working in a research lab offered many opportunities to present themselves and the agreement I had with my supervisor, Professor Burry, was that I could ‘cherry pick’ anything of interest that would be of use for my project.

4.4 Describing the case studies

Following is an overview of seven case studies over the period 2001 to 2004 which employed the development and use of digital and parametric models. In most cases I was the designer of these models, but as some projects grew to include computer programming skills, I worked with others to build the models and design the processes involved. The list of participants and participating firms is in Appendix D. The major case was the investigation between the new and the old at The Sagrada Familia church. This study spanned the entire research period, and can really be sectioned into sub-projects. Fig 4.03 illustrates the relationship of the case studies over time and shows the links between outputs.
Figure 4.03 The case studies over time and the links between output.
The studies used in this research can be categorised in three forms: as practice-based case studies, as pedagogical studies and as an ongoing survey.

All the practice-based research necessitated a degree of travel to a project office or site. The Sagrada Familia research was undertaken both on-site in Barcelona as well as in Melbourne. Similarly, work for The Parametric Bridge included periods of work in London and a site visit to Birmingham. The rest of the work (with the exception of the Jersey Waterfront Bridge, which was presented in London) was undertaken in Australia, in Brisbane, Sydney and Melbourne.

**Case Study One: The Corbertes at The Sagrada Familia**

As I outlined in Chapter Three, one of the expected outcomes of the research of particular interest to the Construction Committee of The Sagrada Familia was to be provided with information from which to build a section of the church, the first connection between the work based on Gaudí’s final forms and the existing building. Undertaking this research work served as the major case study and impetus for the other case studies, and focussed the project towards extending the principles established at The Sagrada Familia to contemporary architectural praxis.

Case Study One is the major case study and is composed of several projects that in all spanned the entire length of the PhD research (Fig 4.03). The work is primarily concerned with the complex forms Gaudí explored during the last twelve years of his life, and the provenance and preservation of the surviving plaster models, such as the model for the designs of the roof – the Corberte model. I spent many hours with the model that dated from Gaudí’s time, and I have expanded this introduction to this case study to describe my research into the history of provenance of the Corberte model. The description of the model itself is in the following chapter.

**The extant model for the roof**

**The model’s provenance**

The provenance of the Corberte model (Fig 3.02) is not entirely clear. The conservation process has reconstructed three of the original Corberte models from the surviving fragments. One is in the museum at The Sagrada Familia, another is used by the Technical Office and the third – which is also the one the Technical Office considers the others were cast from – is in Australia and used in this research.

The model consists of an assembled amalgamation of hyperbolic paraboloid and planar surfaces expected in Gaudi’s mature work, with a variety of openings and protrusions, some of which lie with dependency on surfaces through location on the intermediate lines of ruling.
There is no definitive dating for the Corberte model, but it has been estimated to be about 1923. As Gaudi’s final version for the roof module, its evolution can be roughly placed through the consideration of a variety of sources that place it at either the third or possibly fourth generation of the roof design.

It is possible to chart the evolution of the Corberte model with reference to photographs and drawings; notably in the form of a set of comparative sections prepared by The Sagrada Familia’s Technical Office at the intervals 1898, 1915 and 1918. (Fig 4.04) These sections, cutting through the central nave, illustrate the development from its neo-Gothic incarnation through to the introduction of ruled surfaces. The three periods though are not definitive and the drawings date from the 1950s, so subsequent research, such as the opening of the Sugranyes archive, can more precisely date changes.

Figure 4.04 Half traverse section through the central nave for the years 1898, 1915 and 1918. Drawing prepared by the Technical Office in 1950s.

The benefit of the sections are their service as a time capsule, preserving the state of knowledge at a point in time when the painstaking work of reconstructing fragments of plaster models had only just begun. This might explain why another section was not added to include subsequent iterations of the model dated after 1918 and up to 1925.
Bergós offers three distinct periods in the development of The Sagrada Familia: pre 1914, 1914 – 1918 (when the site came to a standstill and the arboreal forms developed), and 1919 – 1926 (as an extended period of refinement) (Bergós Massó & Llimargas 1999, p. 69). These distinct periods do not correspond directly with the three sections. During the research these sectional drawings were examined against other evidence to note the following variations.

The central roof began in a neo-Gothic guise (as did the rest of the church) with a steep gable and an uninterrupted ridge line. Shown in an elevation dated from 1902, the roof features dormer skylights located midway between the pinnacles of the upper windows (Bonet i Armengol 2000, p. 24). This elevation contradicts the Technical Office’s section depicting the work in 1898, where the tower is included; a premature move possibly by at least five to ten years (Fig 4.05).

Figure 4.05 The straight ridge line in an elevation dated from 1902. With elevation and revised 1898 section details.

The earliest photograph of a model of the roof is dated at 1910, being contemporaneous with the polychromatic model Gaudí made for the Universal Exhibition of 1878 in Paris. For the
most part still displaying neo-Gothic pointed arches, this model adds a central tower capping the ridge line per grid module. This tower appears to be a not-too-distant cousin of the small towers above the cloister bays adjoining the Nativity Façade (of the same period) (Fig 4.06 and an inset figure of the cloister towers).

Figure 4.06 Church model dated at 1910.

The Technical Office’s second comparative section, dated at 1915, indicates the general spread of hyperbolic paraboloid surfaces and the inclining of the central columns. This work post-dates the culmination of the Colònia Güell church project and adopts many of the conventions developed there, thus explicating the view of the Colònia Güell as the laboratory for The Sagrada Familia.

The third Technical Office section is only dated three years after the second – 1918, so I estimate that during this period the Corberte module evolved into its current form. The ridge line is replaced with ruled surfaces converging at an apex upon which a revised tower sits, no longer resembling the earlier cloister tower. The dormer skylight has been removed, replaced with six smaller skylights cut into the Corberte surfaces and covered with hyperbolic paraboloid hoods (this is confirmed with later photos of the model rather than the Technical Office’s drawings). A pyramidal skylight on the lower side aisle roof has also been introduced.

In the absence of definitive dating, this three year period is the best guess for the initial development of the Corberte module in its final guise. The estimate by Professor Burry of 1923 for the last version places some emphasis on the refinement of the work between 1918 (from 1919 according to Bergos) and 1925, when the final model of the church was constructed.

The general impression given by the comparative sections is of change slowly wrought from
the ground up. A subsequent section that could follow is also from the Technical Office (Fig 4.07). This section shows little change at the central roof level, but again from below further refinement is typified by the removal of the upper level balcony, leaving the central columns free from encumbrance until they meet the aisle ceiling. The roof above the side aisle during this period seems to have found a solution to seal it against the pinnacles of the aisle windows and conduits to channel water had been introduced between the two roof levels.

Figure 4.07 The Sagrada Familia church. Half traverse section through the central nave as it is being constructed, in broad accordance with the final model of 1925. Drawing prepared by the Technical Office (with amendments).

The difference between the continuous ridge and the later modular variant was also one of material. Gothic cathedrals are typically roofed in timber, over the central vaults of the nave. The weakness is their combustibility. Gaudí was reportedly proud that his double roof – nave vault and roof – was to be made of stone. Bergos describes it as ‘a feat which, in the past, had never been accomplished’ (Bergós Massó & Llimargas 1999, p. 77). The feat was due to the method that Gaudí had structurally optimised to carry the increased loading of such a roof to the ground – another example of the influence of the Colònia Güell experience.
References to the Corbertes in literature

There are few textual references to the Corberte module. The first was by Rafols in 1928 (Rafols 1928). ‘The hyperbolic paraboloids also form the roof to the central nave and the coincident points [70 metres] join the gables over the central nave clerestory windows’.

The coincident point referred to by Rafols is the point to which the hyperbolic paraboloid and planar surfaces of each Corberte module converge. These points, located virtually above the model, are used to locate the guiding surfaces and are referred to as ‘virtual points’ in the research.

Collins (1963) expanded more fully on the roof in general. His referral to hyperbolic paraboloids as handy roofing surfaces follows the enthusiasm of the period (mid-20th century) for the covering of large spaces with these surfaces, as well as dome structures, particularly well evidenced by the work of Felix Candela (Candela 1954). ‘Hyperbolic paraboloids, those handy roofing surfaces which he had intended to use to vault the nave in his earlier plans, were in the final design to be used only where a closed roof is necessary, as in the upper superstructure’ (Collins 1963, p. 84).

The material I unearthed during the research represents only a fraction of what is available on Gaudi but was essential for reference as I investigated the parametric design for the Corbertes.

Case Study Two: The Jersey waterfront bridge competition

The next case study I worked on was the Jersery Waterfront Bridge case study, a competition project for a new footbridge to provide access to the development of the St Helier waterfront area on the Island of Jersey.

This was the first project in which I worked with other parties, being the architects Michael Hopkins and Partners (who in turn were working with engineers, Flint & Neill). The significance of the work was that the parametric model was developed and then shaped largely through email conversation between the three main parties: architect, engineer in the UK, and researcher in Australia. Unfortunately so early in the research, no research agreement or ethics approval was in place to use the work; however, the case study was significant in two areas. It introduced me to the conversation through the model that was possible between architects and engineers, and I was intrigued as I translated the emailed conversations into parameters in the model of the bridge.
Case Study Three: The Parametric Bridge (I & II)

The two Parametric Bridge case studies were for the pedestrian bridge at the Selfridges store in Birmingham UK. Future Systems were the architects, and the research project was undertaken with Arup London Group Four and facilitated by Dr. Chris Luebkeman from Arup Research and Development.

This Parametric Bridge project was selected because it offered the opportunity to design a parametric model constrained to its method of fabrication. The curved and seamless bridge was a difficult form to realise. Arup London Group Four had been supplied with a digital model by the architects and a fabrication method was sought through the tendering process. A revised model was then built by Arup which conformed to the selected fabricator’s
requirements. It was transformed into an analysable mesh and analysed structurally. This procedure took one person, working on it exclusively, three months to complete. While it could be expected that subsequent iterations would not take as long, a considerable investment in time would still be required, and at a significant cost. The aim of the first case study was to investigate this process with a parametric model, so that in close to real time, iterations of the bridge could be generated, thereby realising the design space that using explicit modelling would have been rendered opaque and unexplored.

The first case study ran parallel with the actual bridge project and so mirrored changing constraints to the parametric model as they occurred on the project. Upon completion in late 2002, I presented the results of the Parametric Bridge (I) to the broader Arup community in London. As I mentioned earlier in this chapter, the idea of this project as a contemporary digital version of Gaudi’s hanging model occurred to me and I discussed the idea with Arup. After an interval of approximately six months, Arup took up the idea and asked me to pursue the Parametric Bridge (II) as an investigation into whether a parametric model could be used simultaneously by two disciplines, in this case engineers and architects. I consider the Parametric Bridge (II) to be the most significant case study of the research. It certainly has had the biggest audience impact.

The Parametric Bridge prompted me to think about how sub-contractors working in the construction sector might use the information generated from parametric models, and I pondered that if they too worked with parametric models, how might that affect the organisation of construction. The result of that research is the focus of Chapter 7 of this work.

**Case Study Four: Docklands Tubes**

Following from the Parametric Bridge (I) in which the manufacturing constraints were applied to a parametric model of the architectural geometry of a pedestrian bridge, another project entered the SIAL laboratory which offered to extend the research.

The Shoal FlyBy was a project for Melbourne’s Docklands which had been won in a competition by the artists Michael Bellemo and Cat Macleod with a series of five maquettes scaled at 1:100 posited along the edge of the waterfront to depict the form and movement of surfaces in water.
Bellemo and Macleod had made the maquettes by hand from bending and soldering electrical fuse wire. The models were, and remained, the master document throughout the process. This case study is the only one not to have a parallel process as there was really no other effective method for describing the work for construction than that developed through the research.

I saw three opportunities with this project. The first was to expand the use of measuring devices for the translation of physical models into 3D. This test was especially relevant for the Corbertes model at The Sagrada Família.

I also saw the potential to expand the project to a team working on a parametric model. Up until this period I had been largely working alone. However, with Professor Burry, I approached Peter Wood, a colleague from Wellington New Zealand, to help define the algorithm for the process. I also used the funding secured from the artists to employ two students to test different methods of measurement.

The third opportunity was to begin the process with the team who were going to build these sculptures. This team consisted of a tube bender and a fabricator. The tube bender took lengths of steel tube and, using computer Numerical Control (CNC) machinery, cut to length and bent sections of tubes. The fabricator then assembled the pieces. Working, indeed collaborating, with the fabricators and constraining the design process to fabrication tolerances was a step beyond Parametric Bridge (I) where the fabrication constraints were defined prior to the
parametric model.

The measurement and planning for the process is discussed in Chapter 5 and the implications of working with those who produce the work is discussed in Chapter 7.

**Case Study Five: Digital stereotomy**

Case study five was the Australian War Memorial in London, investigated for the design of a parametric model drawn from information expressed in architectural drawings.

The memorial is a curved stone wall generated through two overlapping radial grids that gave effect to a tiling pattern in which every piece of stone has a different shape. The architectural drawings described the overall geometry of the wall, and gave the ‘recipe’ for the process of generating the grids, as well as some approximate dimensions for the stone tiles.

![Figure 4.11 The curved stone wall.](image)

The case study emerged when the scale of work required to describe the stone tiles became clear during the project. Of particular interest as a case study for my research was the parallel processes in place. The wall tiling description of the War Memorial was made declarative through computation and tacitly through drawing.

The significance of the research lies in the examination of a specific design response with the flexibility to accommodate changes and testing modes of communication to convey architectural intentions. This design is discussed in Chapter 5.

The complexity in the geometric structure of the wall was introduced at its very conception, being planimetrically generated through two overlapping radial arrays. One array locates the set-out of the segments of a rear boundary wall at even spacing. The second array determines the tiling layout in relation to the boundary wall segments but converging at another point (Fig 4.12).
Figure 4.12 The planimetrically directed process.

To follow these double geometries, one can imagine the implied vectorial direction of movement – from the centre of the first array to the boundary wall, and then back to the centre of the second array. This movement effects a distortion in the tile segments as they focus on a point no longer at the centre of their generating radius. This twisting is coupled with staggered joints at non-uniform spacings between the tiles and combines to produce a pattern in which every stone tile is a different shape.

The rules governing the design procedure were gleaned from the drawings, so the beginning point between architect and computer scientist was the architectural decoding of the drawn information. This need initiated the pseudocoding to which both parties contributed for the development of a declarative computational process in parallel with the design description expressed in the drawings.

Case Study Six: Space Division, the regular irregular façade

The case study for the façade of the Beijing Olympic Pool, or ‘Watercube’, was undertaken with Arup in the very short period of time that the project was allocated for schematic design. Arup wished to investigate alternative descriptions for the facade, which appears from the outside as bubbles of giant proportion encased in a rectangular box.
This case study contributes to the research as it seeks to describe the façade through a set of parameters that can be varied and continue to seek to standardise some elements. This work is about expanding a possible design space through the development of a parametric model. The work is described in Chapter 6, and the implications of the rules that were prescribed to standardise the elements are further discussed in Chapter 7.

Case Study Seven: The Suspended Arc

The Suspended Arc case study was for the development of a parametric model that could embody parameters and constraints as they were updated following several conversations were had between a governmental development agency, statutory authorities and an artist.
Figure 4.14 The Suspended Arc.

The project relates to the Docklands Tubes and the Jersey Waterfront Bridge in that it was both about measurement from an artist’s maquette, and that the dialogue surrounding the project helped develop the parametric model. The Suspended Arc remains unbuilt.

The importance of this case study was twofold: parameters were developed and adjusted as project information flowed during the design development process, and this was the first project in which I combined a parametric model with an editable database and a generative process by programming the software. The work is discussed in Chapter 6.

4.5 Conclusion

In this chapter I introduced the design of the research. The chapter included the hypothesis that the design for the parametric modelling of complex forms at The Sagrada Familia church in Barcelona can reveal lessons for how architects can better understand the adoption of parametric design in architectural praxis more generally.

I introduced the case studies used in the research and explained why each had been chosen. An expanded description was given to the major case study, that of the new to the old at The Sagrada Familia church in Barcelona and the original model of the roof design that was used in the research.
Endnotes

1 I am deeply indebted to Dr Anitra Nelson, Research Fellow at the Australian Housing and Urban Research Institute at RMIT University, for her guidance in enlightening me to the characteristics of social science research which could be of use to the designer engaging in research.

2 A date estimated by Professor Mark Burry when asked by me during a discussion about the research.

3 The archive of Domènec Sugranyes (Gaudi’s senior assistant after the death of Francesc Berenguer in 1914) has provided new photographs of the models and has only recently been opened. (Bonet i Armengol, J 2000, *The essential Gaudi: the geometric modulation of the Church of the Sagrada Familia*, 1a edn, Editorial Portic, Barcelona. p.126).

4 Bonet refers to a photo from the Sugranes archive that appears to have older features to the columns, and so is probably from the period after 1918 and before 1925. (Figure in following chapter.)

5 The full quote is: ‘He had the advantage over his predecessors of not needing buttresses and abutments and of having created a double roof of stone, one that is completely non-combustible, with the outer surface stronger than the inner one, a feat which, in the past, had never been accomplished.’


7 Collins used the word ‘gorge’ to mean perforation.
Chapter Five Designing the design

Introduction

I suggested in Chapter Two that to design parametrically required a greater amount of effort to structure a design earlier in a project. The aim of this chapter is to examine how a parametric design is formulated both by gathering appropriate information and by implementing a design strategy through the development of a schema.

To achieve this, the chapter is divided in three sections. Section 5.1 introduces methods I experimented with for capturing existing model information, primarily through three-dimensional measurement. Case study findings are used to inform and demonstrate these methods. Section 5.2 discusses the considerations given when structuring the schema, with reference to the elicitation of constraints. In the first two sections I begin with research related to The Sagrada Familia and then I show how this has been transferred to the other case studies. Then in Section 5.3, I detail how the elements of the first two sections are combined in an investigation into the skylight openings of the Corbertes model from my major case study.

Case studies used in this chapter

The following four case studies outlined previously are used in detail in this chapter; the Corbertes at The Sagrada Familia, the Parametric Bridge (I), the Docklands Tubes and Digital Stereotomy. I have used all four case studies to illustrate how I define parameters and constraints. In particular the Corbertes at The Sagrada Familia and the Docklands Tubes serve to demonstrate how measurement can be used at a variety of scales to provide information, especially where the parametric model is preceded by a physical scale model.

The chapter begins with measurement and then focuses on constraint definition although, in reality, the acquisition of measurement data serves to define constraints and so the discussion on constraints is not easily separated within this chapter alone.

5.1 Three-dimensional measurement

Background work to measuring scaled physical models

Case Study One, for the Corbertes at The Sagrada Familia, was formulated in the ARC grant New onto Old as a study of the connection between the church’s transept roof and façade; from the digital to the real. The intention of the research was to investigate how flexible a parametric model could be when matching it with the existing built fabric and conditions as found on site at The Sagrada Familia church. In the grant, the digital was posited as the precise and the existing built work as the imprecise. The test was to be one of real-world conditions; so that we might learn how useful parametric models could be, especially when dealing with existing structures, as is so often the case in construction.
I made use of three-dimensional measurements at differing scales, from digitally scanning Gaudí’s original model scaled at 1:25 to gathering site information in Barcelona using digital terrestrial scans and photogrammetry (measuring through photographs). Figure 5.01 indicates how the play between what is really the old (the plaster model) to the new (digital model) to the old (existing site conditions) made the relationship between what was old and new, and at different scales, rather more complex.

Figure 5.01  Old and new, real and digital, at different scales.

The real existed at either end of the spectrum – as a physical model encoding Gaudí’s schema and as a full scale building. The means of measurement became the glue between the digital to real and real to digital. During my research it became apparent that a major focus was in fact designing the parametric design, so that relationships could be negotiated between old and new, real and digital.

The dataset for developing the parametric model for the Corbertes consisted of a knowledge of Gaudi’s codex of ruled surface geometry (acquired through the tutelage of Professor Burry and the application of which is explained in Section 5.2) and his original model for composition and reference. The original model has in fact been reconstructed and reassembled from pieces (Fig 5.07). Although there is no record of the process of its re-piecing, patched lines on the external surfaces give away the fracturing it suffered in the church burning of 1936 when, during the Spanish Civil War, Gaudí’s models were smashed and his drawings burned (Bonet i Armengol 2000, Burry 1993).

The archive at The Sagrada Familia, to which I made several visits, has thousands of model
fragments in its collection. In trying to expand the selection of modelled components I could consider, especially where parts of the Corbertes model are missing, I asked for and received a box of fragments from the model archive at The Sagrada Familia from which I could augment my data.

Figure 5.02 A box of model fragments from The Sagrada Familia archive.

Before my involvement with the Corbertes there had been a project to digitally reconstruct the model and early on I realised that there was quite some variation between the physical model and this earlier rebuilt counterpart 1. That project had utilised a digitiser on an articulated-mechanical arm that functioned to locate three-dimensional points in space through manual touch, so that edges, boundaries and corners could be identified.

Copyright works removed

Figure 5.03 The earlier digital construction of the Corbertes model approx 1999. (Credit: Professor Mark Burry).
My intention was to undertake a more ‘forensic’ analysis of the model so that I could study the surfaces Gaudi had employed and use the detailed information to design the parametric model. I also wanted to assemble the various discrete components I had collected and use the information as a reference to which the parametric model could be referenced. After researching three-dimensional measurement and finding several systems that could possibly gather the surface information that I was interested in testing, my aim was to design from a fully scanned and digitised version of the entire original model.

**Techniques and tools**

Over the period of research I investigated and tested many systems for gathering three-dimensional information. I was interested in both close range (for the model) and long range data acquisition (for measuring on site). Close range scanning is closely associated with, and has been most directly developed for, reverse engineering; the process of digitally capturing existing physical objects for product development. When talking with people working in the area I found this situation arises because the original design documentation has been lost or never existed (items that are handmade are one example).

Similarly the complex digital modelling undertaken by the architectural firm Gehry Partners is determined through the primacy of the physical modelling methods used in the office. Glymph et al (2002) show how Gehry Partners used parametric design to describe freeform glass structures.

In my research, Case Study Four, the Docklands Tubes, drove the specification for a close range three-dimensional scan. Case Study Four took place prior to my research on the Corbertes model (Fig 5.04). The five models, which were the sole data source for this case study, were made by the artists from soldered electrical wire prone to deformation at the slightest touch. With two students, I tried different methods of trying to accurately and effectively measure the physical models. Beginning with a point probe on a three-dimensional digitising arm, repeatability of the measuring the position of the wires on the scale model proved inaccurate. The flexibility of the wires was such that methods, that included touching them, was difficult. This difficulty led to the use of a non-contact method using a laser scanner attached to the end of a digitising arm. The laser scanner returned digital versions of the models as sub-millimetre clouds of points.
I tested several three-dimensional laser scanners for close range data gathering. These laser scanners consisted of an optical scanner which is fixed in position and captures data as it is rotated on a wheel. I also tested a line scanner attached to a articulated-arm as an accessory to a point probe and a portable handheld scanner that stands alone and uses a remote sensing antennae as a reference. Each system has positives and negatives and digital data acquisition is an area in rapid development. I was fortunate to be able to specify some equipment that RMIT University purchased and I selected the line scanner as it fitted to an existing articulated-arm. Being fitted to the end of such a mechanism gave me several degrees of freedom to be able to move around objects and scan. I also purchased a portable scanner and I took it with me to The Sagrada Familia on a number of occasions. Figure 5.05 shows me scanning fragments of Gaudi’s models in Barcelona. The limitation of the portable scanner was that it used an electromagnet for its origin and data acquisition was limited around metallic objects. The portable scanner and the algorithms it used were developed at the University of Canterbury in New Zealand and I was fortunate to establish a research relationship that included access to researchers and their development software.

I also tested equipment for long range scanning for the existing, but inaccessible, parts of the church (discussed in Chapter 7). The two scanners I tested were a phase-based scanner and a time-of-flight scanner.
Figure 5.05 Techniques and tools of measurement used in my research.

Scales

The Corbertes model serves as an intermediary for the design of the transept roof, frozen at the smallest scale Gaudí used for investigation. Gaudí’s use of scale, first at 1:25, then 1:10 and on to full size, was a process of representational refinement. The model as a geometrical composition occupies an interesting position in this regard, located part way between a technical document and a maquette (such as those for the Docklands Tubes – as a sculptor might use for preliminary investigations).

Robin Evans made a distinction between sketches and models in painting and sculpture, and drawings in building. His position was that painters and sculptors enjoyed a much closer relationship with their chosen media than architects, who by way of drawings were removed from the construction of buildings; a position that did not necessarily constitute a disadvantage for architecture but significantly altered their position during the execution of a work. Evans argued that the contrast between the early studies of painters and sculptors considering architecture a visual art did not preclude change during the execution of a piece, but rather provided ‘sufficient definition for final work to begin, not to provide a complete determination in advance, as in architectural drawing’. (Evans 1997, p. 156) This flexibility was so for the Docklands Tubes as the artists’ instructions were that the curves in the Docklands Tubes need not be adhered to strictly, but were there for reference. There was not an assumption that they be scaled to exact replicas.

The rigid adherence to mathematical geometry makes it is difficult to place the Corbertes model firmly as an artist’s maquette in the sense Evans espoused. The surfaces are in fact
determinant of the intended construction, although the propensity Gaudí displayed in his built work to continually adjust and instigate change can only raise speculation as to the finish and texture of the final roof form. The process of ‘scaling up’ to 1:1 was first made during the 1990s, when the first ruled surfaces were constructed at The Sagrada Familia in plaster at full size. Moulds were cast for the forming of reinforced concrete and the reinforcement followed the lines of ruling. This technique is still in use, being the latest example of reinforced concrete since Gaudí first made use of it at Park Güell. Burry (2002) gives an account of the various ‘scaling-up’ processes used at The Sagrada Familia.

Gaudí’s modelling scales (of 1:25 and 1:10) have the equivalence in architectural drawing to that usually reserved for the detailed description of a structure. Such drawings are usually partial and refer to portions of the building that might be typically repeated and/or require special attention. The partial nature of what can be represented is constrained by the medium of the drawing sheet. Working at 1:10 is a magnification of two and a half times the detail required at 1:25; a plaster model at this scale effectively becomes a small building (Gaudí did build assemblies several stories high). The Corbertes model at a scale of 1:25, by comparison with the scale of 1:10, is engendered with a deliberate vagueness, although when the placement of a fractured piece of plaster is reset, it might be moved a few millimetres, here or there, resulting in considerable variation.

**The original model**

The roof at The Sagrada Familia consists of a series of repeated modules. Gaudí proposed The Sagrada Familia have a similar roof over the central nave and transept. The underlying surfaces of the plaster Corbertes model form one of the modules, and an assembly of modules would make the roof.
These roofs are modular and punctuated with skylights, which are intended to emit indirect light through to the interior of the church via the openings in the ceiling, largely constructed from hyperboloids. The light will pass through the circular centres of the hyperboloids, all curved surfaces which will effect a softening of the sun’s rays. Through the digital reconstruction of the original model I found a method of learning about the design process Antonio Gaudí applied to the Corbertes model.

The Corbertes model, as it has been physically reconstructed, represents one half of the roof module; the module being repeatable within the 7.5 metre grid used at The Sagrada Família church. (Fig 5.07). After it suffered in the church burning of 1936, the model’s process of reconstruction privileged the external surfaces over the interior where the plaster gluing remains exposed (inset Fig 5.07). As a partial assembly of a full module, the model gives both a nod to where it is going as well as the route travelled. The potholes in this path have resulted in scarring, which at the scale of 1:25 has affected the partial obscuring some of the detail that would have been once evident in the model. It is particularly worn along edges and joints.
Figure 5.07. The original Corbertes model. Inset shows an internal detail.

**Elements of the Corbertes model**

Figure 5.08 shows a detail of the scanned version of the Corbertes model. I used the line laser scanner fixed to the articulated mechanical arm to scan the model. The process of scanning was repeated during the research as I focussed on specific areas. In Section 5.3, I show how I captured digital information from which to design the parametric model for the openings, but the first scanning campaign was to identify the underlying surfaces as distinguished separately from the openings and protuberances. These surfaces, as they are found in the model, are partial, cut from the full ruled surfaces that guide the module, and with the exception of one hyperbolic paraboloid meet at a virtual apex above the model (shown as the virtual point VP in Fig 5.09).
Uncovering the full extent of the guide surfaces of the roof module was essential to prefiguring the design of the parametric model and almost all the apexes of these surfaces have been removed as they extend beyond the Corbertes model. These apexes become virtual points, found by following edges of the model’s surfaces. Figure 5.09 shows the vertical virtual point (VP) of the Corbertes model.

I have nominated all the surfaces, openings and projections I identified from my process of measurement and they are as follows:
Figure 5.09 Identifying Corbertes elements from the original model.

The main surfaces

The surfaces are derived from the guide surfaces and consist of two versions of hyperbolic paraboloids and a planar surface which is located between.

(HP1) Hyperbolic Paraboloid surface One
(HP2) Hyperbolic Paraboloid surface Two
(HP3) Hyperbolic Paraboloid surface Three
(PS) Planar surface
(VP) Virtual Point where the two hyperbolic paraboloids HP1 and 2 and the planar surface PS meet
Openings and Projections

These openings have been related to the surface characteristics of the surface type upon which they are located. For example, the openings on the hyperbolic paraboloids use ruled lines for location.

(S1) Ruled opening on HP1

(S2) Ruled opening on HP2. This is similar to the ruled opening on HP1 and is not complete.

(S3) Planar openings. This series of skylights are located on the planar surface.

(H1) Hexagons

(H2) Large hexagon

(CT) Central lamp tower. These are incomplete.

Openings and projections

There are three groups of elements on the Corbertes module – two sets of openings which both penetrate the roof’s thickness, and a series of hexagonal shields. Of these shields, the four smaller (H1) on HP2 are inscribed with the liturgical expression ‘al—le—lu—ia’ below ‘amen’, inscribed on a larger shield that wraps around HP2 and the planar surfaces.

The larger shield (H2), with its symmetrical companion, effectively caps the main surfaces of the Corbertes. A lamp tower stands above, although only the base of this tower survives on the original Corbertes model (CT).

The shields are related to those on the tower finials of the Passion and Nativity facades, emblazoned with ‘hosanna’. On the towers, the shields with their extruded hexagonal forms, serve as the intermediary between the paraboloidal towers and the polyhedra form of the finials.

Gaudí’s codex and the Passion façade

I ran quite a few studies in measurement at The Sagrada Família. Appendix A contains a paper I wrote entitled Hybridised Measurement (Maher, A & Burry, M 2002) in which I explained the use of a variety of measurement techniques to gain three-dimensional information for the facades at The Sagrada Família. After writing that paper, I decided to run an experiment to test the validity of comparing information from a scaled model to the real size on the Passion Facade, which was constructed during the 1970s and 1980s.
Figure 5.10 The base of the Passion Façade with the original drawing inset.

Figure 5.11 Scanning the Passion Façade model.
I wanted to test the methodology for measuring the Corbertes surfaces, and I also scanned the full façade model for the Passion Façade as shown in Fig 5.11. I was interested in whether I could extract the data sets of Gaudí’s codex and the three-dimensional scan, with sufficient description for a student to rebuild. I had a remarkably capable landscape architecture student working for me for a couple of months and, although it was no quick task, upon the third review of the work the student asked how to get more curvature to some of the hyperbolic paraboloid surfaces.

![Modelled surfaces for the Passion Façade columns. Pseudo hyperbolic paraboloids have been left blank.](image)

There were three things to put together here. The Passion façade was only described in a photo of a drawing and this was the basis for the design and construction of this façade during the 1970s and 1980s. The plaster model and the façade are closely aligned; the model in fact dates from that period of design and construction. Through this research into measurement I found the surfaces both modelled and then constructed are in fact made to look like hyperbolic paraboloids from Gaudi’s codex of ruled surfaces. However, in the case of the Passion Façade
columns at The Sagrada Familia church they are not hyperbolic paraboloids; rather they are surfaces that look like those from Gaudi’s codex.

Figure 5.13 Detail of the original Passion Façade model as a three-dimensional digital scan.

This is the first time I have reported the findings. It would be a very interesting social study to understand what the intentions of The Sagrada Familia Technical Office were in the period during the 1960s and 1970s. Did they fully understand Gaudi’s codex? What did Gaudi plan for these columns? How might the original drawing be understood now? Could there be other proposals?

5.2 Schema creation

The previous section introduced the methods with which I experimented for capturing and measuring existing model information to inform the parametric model. This section discusses the considerations given when structuring the schema, with reference to the elicitation of constraints. All four case studies I refer to in this chapter are used in this section. They are the Corbertes at The Sagrada Familia, the Parametric Bridge (I), the Docklands Tubes and Digital Stereotomy.

While eliciting Gaudi’s codex of surfaces from the Corbertes model at The Sagrada Familia determined the structure of the design for that parametric model, the other case studies provided me with different points at which to begin their schema definition. In my research I found two predominant methods of schema creation were schemas based on eliciting rules based on methods of fabrication, and schemas based on realising geometrical design intent. I
begin with the Docklands Tubes as that case study also relied on a model.

**Schemas based on methods of fabrication**

The models for the Docklands Tubes consisted of a network of freeform three-dimensional curves. The artists had made the models by hand. From bending and soldering electrical fuse wire, the artists had previously built relatively simple curved forms in steel, developing an appreciation of the fabrication processes involved.

The initial schema design grew from this understanding. While the artists understood the methods of fabrication, the researchers designed the process for embodying those methods of fabrication as parameters and constraints into the parametric design. These parameters were sketched out during a series of conversations between the members of team who were going to build these sculptures. The construction team consisted of two separate contractors, a tube bender and a fabricator, and an engineer gave input to the process.

The tube bender explained how he took lengths of steel tube and, using Computer Numerical Control (CNC) machinery, cut them to length and then bent sections of tubes. The fabricator told how he intended to assemble the pieces into curves by rotating each arc relative to the next. The separation of curves into arcs was a process that occurred during the shop drawing process and was fabricated by welding similar profiles of different lengths and radii. The contractors had a deep knowledge of their craft – and explained the modern process of tube bending has its foundation in the 14th century when developments in methods for bending brass resulted in a musical horn of conjoined tubes – the forerunner to the trumpet. Today the bending of tubes can be accomplished through highly controlled CNC processes where the tube passes either through rollers or around a fixed die. Most bends are planar and of fixed radius, although it is possible to offset the radius to draw helical extrusions.

The difficulty with building freeform curves is that they are continuously changing in radius, whereas an arc is of fixed radius. However, by connecting a series of smaller arcs with a tangential relationship, a curve can be approximated. Further, where the arcs meet at a point of tangency, rotation can be introduced to make a three-dimensional curve. Through their own research the artists knew that without establishing tangential relations between the constituent parts of the work (the various lengths of tube), the result would be relegated to an exposition of joints, preventing a reading of the whole – in this case the network of freeform steel tubes.

We discussed how, by twisting tangential arcs relative to one another, it is possible closely to emulate the construction of fully three-dimensional curves. I had had students trace the curves from the point cloud scan of the model. Automotive exhausts made from several bends and straight tubes welded together in this manner are probably the most complex curves now constructed. A similar application in architecture would be the fabrication of continuous hand rails.

The research in the Docklands Tubes schema was intended to develop a design for a parametric process that transferred scaled freeform curves into digital space, transcribing the
curves as tangential arcs for a computer numerical controlled (CNC) tube bending operation, followed by fabrication through their full size and spatial relocation.

Figure 5.14 Approximating curves using arcs for the Docklands Tubes.

The design for the parametric design of the Docklands Tubes evolved from, and finally embedded, the discussions of all parties involved. The significant discovery for delivering parametrically informed architecture was the development of an algorithm that embodied fabrication constraints, and thus facilitated the compression of many processes found in a construction project into one stage at the beginning of design.

The algorithm involved assimilating the information required by the tube bending machine, and for the fabrication procedure, with a method for separating the freeform curves to arcs. The algorithm developed as visual iterations were made, finishing with eight constraints. The parameters that could be varied for each curve were minimum arc length, radius and maximum curvature change. I describe the process for making design iterations in the next chapter, but for now I will briefly describe how the fabrication process influenced the parametric design for the Parametric Bridge (I).

As I described in the introduction to the Parametric Bridge, the effort to parametrically design a model for the bridge could be directly correlated into savings in time and effort for the bridge’s designers, Arup. By the time I began my research, Arup had already been through the process of making an explicit digital that conformed to one method of fabrication, a procedure that Arup calculated took one person, working exclusively, three months to complete. The aim of the research for a parametric model of the bridge was to be able to explore further
variations of the form and this could directly relate to commercial costs which may prohibit iterations of a design from being investigated.

Figure 5.15 Explicit model supplied by Arup (three months effort).

The bridge’s underside or tray is steel and the canopy is polycarbonate supported by steel hoops at varying angles from the deck which rises and falls gently to suit disabled access. The bridge is a complex form as it is curved in two directions and so Arup had sought a fabrication method through the tendering process. Only one acceptable method to the design team was found. This method was based on bending three steel tubes (two side tubes at the deck’s edge and a main tube on the underside). These steel tubes were to be bent in two directions to achieve the three-dimensional form of the bridge’s tray.
I began my research by extracting three guiding curves from the edges of the tubes in the explicit model. These curves resided at the top of the geometric database of the parametric model, so the parametrically variable tray could be varied to suit different tube sizes while maintaining the bi-tangency of the sides within the boundaries of its perimeter. The polycarbonate canopy followed suit, depending on the successful regeneration of the tray but also operating within its own fabrication constraints. (These are not described here but can be found in Appendix A: Maher & Burry 2003).
The curves were used to guide the parametric surfaces but later proved to be overly constraining, as I discuss in Chapter 6. I did not visit the fabricators and so the discussions on fabrication constraints were between me and Ed Clark from Arup. Ed made sketches and described in words the process and I transferred that into the design for the parametric model. At one point I made a three-dimensional scale model of the ruled surface that was placed between the tubes, (Figure 5.17) which could be then developed or unrolled with little deformation and which I presented to Arup in London. This type of surface had not been considered in the fabrication proposal and so it was an early result from the parametric model.

![Figure 5.17](image)

_Schemas based on design intent_

Another predominant method of schema generation is through understanding design intent. I finish this section with the surfaces from the Gaudi codex of ruled surfaces, but first I will discuss the work I undertook for the parametric design for the stone wall at the Australian War Memorial in London; the Digital Stereotomy case study. I could similarly have used Case Study Six, Space Division, here but I have chosen Digital Stereotomy as the parametric design follows the designers thinking and intent as I understood it by gleaning its _formula_ from architectural drawings.

Digital Stereotomy was purely theoretical. The research arose almost at construction (shop drawing stage) where the outcome of the design was already finalised but its realisation was an extremely difficult process due to a complex form. As I described in Chapter Four, this project investigated a method for describing individual stone tiles in a curved wall where each piece was a unique shape (Fig 5.18).
Figure 5.18 The curved stone wall of the Australian War Memorial.

The opportunity to conduct this research arose as a consequence of the extrapolation of a design process embedded as a diagram and textual notes within completed architectural documentation. It had become evident that the two dimensional drawings themselves were inadequate for describing the complex form (Fig 5.19). This shortfall resulted in a dramatic increase in the scope of shop drawing the stone tiles. The expanded proportion of time devoted to establishing the corr at the scale of individual tiles revealed itself in the cost to undertake the work and the pressure on time constraints on an already tight program schedule.

Figure 5.19 The schema was devised from written notes (inset) found on the architectural drawings.

The complexity in the geometric structure of the wall was introduced in its very conception, being generated in a plan view through two overlapping radial arrays. One array locates the set-out of the segments of a rear boundary wall at even spacing. The second array determines the tiling layout in relation to the boundary wall segments, but the second array converges at a different point. Figure 5.20 illustrates a diagram I created to explain this process of generation, and Figure 5.21 shows it in action. It was developed from reading the architectural drawings.
Figure 5.20 The planimetrically directed process.

To follow the rationale of my diagram, one can imagine the implied vectorial direction of movement – from the centre of the first array (the wall set-out) to the boundary wall and then back to the centre of the second array (the tile set-out). This movement effects a distortion in the tile segments as they focus on a point no longer at the centre of their generating radius. This twisting is coupled with staggered joints at non-uniform spacing between the tiles and combines to effect a pattern in which every stone tile is a different shape.

As I said, the rules governing the design procedure were found in the drawings, and I worked with a computer programmer to develop an algorithm that could computationally follow this design intent and construct the wall as a three-dimensional model. The beginning point between architect and computer programmer was the architectural decoding of the drawn information. This initiated a project of documenting the understanding from both disciplines as a pseudocoding exercise to which both of us contributed for the development of a declarative computational process that embodied the design intent as I found it expressed in the drawings.

Figure 5.21. Illustrating the process

The research extended to parametrically describe how each tile is generated – there are three
different types and the architectural details on the drawings showed the set-out points for every stone tile along each segment’s cross-sectional plane. I recorded this information in a spreadsheet (Fig. 5.22). The design process interrogates this spreadsheet, uses the parameters for the various generation of stone tile type, and then returns information to the spreadsheet with spatial information of each tile. This is the value of the process, but for this section I focus on the effort to construct the schema rather than the results of the process. Figure 5.23 is included to show the process of tile generation. The basic difference is that each type is extruded in a different direction and the algorithm is designed to mimic this.

Figure 5.22 I recorded information in the spreadsheet (left) and the information generated from the design process is returned to the spreadsheet (right).

Figure 5.23 Parametric process for generating tile various types.
The schema design for the computational process to digitally model in three dimensions the geometry of the curved wall used the global parameters of radial set-out and the local parameters of each tile (as it was identified in the drawings). This information was stored in a spreadsheet by position and tile classification. As each tile was drawn, and all its dimensions were determined, the data are automatically extracted and appended to the spreadsheet.

**The Sagrada Familia surface schema**

I finish this section by referencing back to the general schema for the module arrangement at The Sagrada Familia church. Once one is familiar with Gaudí’s geometric codex, it is discernable – at least for the main surfaces – by eye. Sensing through touching the model becomes useful as familiarity grows, but measurement and analysis provided a much more rigorous activity in unearthing the constitute elements of the highest level of the schema.

**The guide surfaces**

As I described in section 5.1, the main extant surfaces upon which the features and openings are located are remnants of full hyperbolic paraboloids and planar surfaces. The exterior surfaces of the Corbertes models have been pared and pruned for the model assembly, from initial plaster surfaces.

These full surfaces were revealed in the original model in Figure 5.09 and are referred to as guide surfaces in this case study for, just as when working in plaster, they are the first elements modelled and their guiding influence remains at the very top of the relational structure of the schema for the parametric model.

*Figure 5.23 Parametric guide surfaces. Hyperbolic paraboloids One, Two and Three (LtoR).*
Virtual points

There are three virtual points for the guide surfaces; the central apex (noted as VP in Figure 5.09), shared between HP1, HP2 and PS, and the vertices of HP2 and HP3 that are also outside the realm of the plaster model. These points are the very highest level definition of both the real and the parametric model. The entire assembly is influenced by the location of these points and, in this regard, if the Corbertes is to be considered a flexible module, then the ability to pick up the entire assembly by these points with all else following would allow its repositioning elsewhere.
Figure 5.25 Virtual points of the Corbertes guide surfaces.

Figure 5.26 Illustrating changing form by altering the virtual points of the Corbertes guide surfaces.
Thus the overall dimension and size of the Corbertes model can be modified through changing the values of the location of the extremities of the guiding surfaces. Figure 5.26 shows the movement achieved by altering the virtual points of the guiding surfaces.

**5.3 An investigation into the Corbertes skylights**

This section of the chapter describes in detail the scanning, measurement and schema definition for the parametric model for the skylights based on the Corbertes model at The Sagrada Família.

There are three skylight openings on each planar surface of the roof module, making a total of twelve of these type of skylights in each module. The skylights are mounted one above the other, and although each opening is different in size there is a proportional rhythm that is clearly discernable by eye. Each skylight is made up of two components, an opening and a hood. The surface upon which these openings penetrate is inclined and therefore exposed to the weather. It would appear the hoods are designed over each opening by Gaudi to protect the skylights and provide some rainwater protection.

![Figure 5.27 Skylights on the planar surface. View of original model – openings coloured.](image)
I made detailed three-dimensional scans of the skylights from the Corbertes model. As for the guiding surfaces of the roof module, the minimum parameters needed are the points at the extremities of the composite surfaces, whether they be planar or hyperbolic paraboloids. However, the surface detail here, as elsewhere, was intended for matching the parametrically defined surfaces against the measured surfaces. When I began the research I was not expecting any further Virtual Points might have been used to construct and locate the surfaces for the skylights.

Once the openings were scanned several tasks were undertaken to reduce the file size. For manageability, tools to give greater effect to the location of edges were used. Algorithms employed by software for scanning clouds of three-dimensional points tend to ‘round’ the data set, with the effect of blurring edges between surfaces. Feature recognition at this level – edges embedded in mesh surfaces – is not well developed, and is still a subject of ongoing research (Smith & Claustre 2005).

The scans were then interrogated, firstly to determine the planarity of the surfaces that visually appeared planar. During this work I found something interesting with the opening reveals. The reveals in this case are the surfaces that penetrate the thickness of the model, from the exterior to interior. They were tapered towards the interior. Early on, I had thought of them as perpendicular to the external surface, and in the earlier reconstruction (Fig 5.03) they had been. However as I laid planes over each, confirming their planarity, I noticed a tapering of the surfaces (Fig 5.30). I found the reveals converge to a virtual point on the interior and when this process is performed on all three (Fig 5.30) they aligned. Even more interesting,
these distances relate to the overall height of each skylight, as I will soon describe.

Figure 5.29 Skylight surface scans. Testing surface planarity by fitting a plane to the scan data.

Figure 5.30 Analysing the three tapering skylight openings.

Each element of the three skylight openings and hoods was then carefully measured and recorded. Figure 5.31 shows the work in recording the information for the middle window.
New line work was modelled over the edges which was especially useful where wearing had occurred and the point of the hoods had all been worn to an extent. I used the overall proportional relationship to design the parametric schema.

![Figure 5.31 Dimensional analysis of the middle skylight opening.](image)

The following figure (5.32) shows the schema definition for an individual skylight that resulted from these investigations and the proportional relationship between all three skylights on a planar surface. The design strategy I employed here was to parametrically encode the geometry for a master skylight which could be instantiated into one of the three positions. As many parameters as possible that could control the skylights were enacted, leaving those parameters that I wanted individual control over to move on their own. An example of this is the angle of the hood. Each hood protrudes at a different angle from the roof and, although so much of the geometry of the skylights is shared, it is a variation such as this that creates the distinctness of each skylight.

Following the schema definition is a diagram I made to show the hierarchical relationship of surfaces and points from the editable database of the parametric model that follow the schema to define the parametric model for the skylight (Figure 5.33). At the top is the point and guide surface upon which they lie, the middle section shows the elements of each skylight and links between, and the bottom section shows the resultant geometry.

The skylight openings are further discussed in this project. In the next chapter I further describe how the parameters for the skylight openings are manipulated to fit the scanned model and relate to the proportion system. I also describe how the parametric model functions so that openings are adjusted to suit the floor levels within the Corbertes when that
Figure 5.32
Proportional analysis of the skylights
Geometric schema definition.
Figure 5.33 Parametric definition of the skylights.
information was provided.

5.4 Conclusion

The aim of this chapter was to capture a narrative about the effort expended and the routes taken to prefigure a parametric design. I did this in relation to four case studies in which I documented the gathering of appropriate information for the implementation of a design strategy, through the development of a schema.

I found, when designing the design, there were two predominant methods of schema creation in my case studies. These were, firstly, schemas based on eliciting rules relating to the methods of fabrication and, secondly, schemas based on realising geometrical design intent. I found the methods not to be exclusive to another, but if combined, one predominates.

I found the boundary conditions relate to the tools, techniques and information at hand. I used sketches and verbal descriptions (with Arup), extant geometry from models, and the architectural drawings for Digital Stereotomy. A schema, it would appear, is much like a recipe; it requires specific ingredients and a systematic method.

Furthermore, in my case study experiments I experimented with methods for capturing existing model information, and the Docklands Tubes primarily drove the specification of measurement through three-dimensional scanning. The application of these techniques to the Corbertes model was the first time a model from The Sagrada Familia had been scanned and it allowed me to forensically assess the surfaces of the form.

Through these experiments this assessment unlocked further knowledge of Gaudí’s choices and methodologies and this has both technical and historical value in light of the loss of documentation. I found discrepancies with an earlier attempt to measure the model in three-dimensions and when testing the process on another model for the Passion facade, I found evidence that some surfaces constructed in the 1970s and that purport to be of Gaudí’s codex are in fact not doubly ruled surfaces.

Considering the considerable effort at the front end of a project when a schema for a parametric model is being designed, the Parametric Bridge (I) offered particular interest as the engineers had calculated the effort required to manually construct the geometry. For the bridge, this was three person-months for the first iteration. While I could not directly compare the time taken to prepare the parametric version of the bridge, as I did not start with the same knowledge, I believe subsequent manual iterations, while not consuming another three months, do not compare with minutes for an iteration from Parametric Bridge model.

Finally, of all the elements I documented on the Corbertes model, I showed the schema development for the guiding surfaces, as well as a detailed investigation for the skylights on the Corbertes model. This investigation elicited not only the detailed proportional system that was employed to create the model and then codified into the schema, but also an indication of how the model may have been originally constructed.
Endnotes

1 Before my involvement there had been an earlier project in the late 1990s to digitise the model using an articulated-arm digitiser. This project located important points and a surface was built from it. It was not, however, accurate. I believe this was a combination of too few measured inputs and a limited knowledge of Gaudí’s codex of ruled surfaces.

2 The close-range scanners I tested were a Konica Minolta optical scanner, a ModelMaker line scanner attached to a Faro articulated-arm, and a Polhemus portable scanner.

3 The long-range scanners I tested were a Faro phase-based scanner and a Leica time of flight scanner.

4 I made observations of assemblies of planar curves that have been used to give three-dimensional effect, described in Maher, A, Wood, P & Burry, M 2003, 'Building Blobs: Embedding Research in Practice', Proceedings of 22nd International eCAADe Conference, Graz (Austria), 17-20 September 2003. Found in Appendix A.

5 Burry has published a series of photographs showing the process of model making at The Sagrada Família. Full geometric surfaces are first modelled before being cut along lines of ruling or intersections to construct modelled assemblies. In Burry, M 1993, *Expiatory Church of the Sagrada Familia*, Phaidon Press, London.

6 Fluted openings over openings are a frequent feature of Gaudí’s well known ‘roofscapes’, the most well known of which is the Casa Milà.
Chapter Six  Traversing parametric design

Introduction

Chapter Five introduced the early considerations that must be made when designing a schema for parametric design. This chapter considers parametric design in action. It reflects upon the potential to traverse a parametric model as a design space as well as opportunities to share the derived design space with other disciplines.

The aim of Chapter Six is to relate the early assumptions of the design prefiguration with the resultant design space. This chapter most directly offers a ‘sense of usefulness’ for parametric design in architectural praxis.

Section 6.1 considers the potential for parametric design as a collaborative tool. It uses Case Study Three, the Parametric Bridge, as a metaphor for a digital version of Antoni Gaudí’s catenary hanging model which was both a physical and interactive tool for architect and engineer collaboration. Section 6.2 reviews the design space of two case studies which try to closely approximate physical models: Case Study Four, Docklands Tubes, and the Corbertes case study at The Sagrada Familia. Section 6.3 examines the nature of the communication when designing, in action, parametrically.

6.1 Collaboration

This section describes an experiment that had its origins at the beginning of the Corbertes research but which was ultimately tested in another case study, the Parametric Bridge (II). As I described in Chapter Five, the Corbertes model could be considered as movement immobilised in plaster, captured by Gaudí through the various physical mechanisms he made for communicating, through visualisation, the codex of ruled surfaces he employed. As I grew closer to realising the Corbertes as a parametric model, I reasoned the digital process I was experimenting with was one of animating the plaster, garnering movement from identifying the complex relationships of surfaces and all the virtual points beyond what existed physically in the plaster model.

As I measured the original model and found the virtual points of the full and partial surfaces, most of which were probably physically arranged on jigs so as to construct the formwork for the gypsum model, I speculatively pondered how the original model could be constructed as a movable structure. As mentioned, Gaudí used tools to describe the form-giving nature of the surfaces he employed, and variations of these tools can be found today in the Technical Office on site. Indeed, I have witnessed members of the Technical Office reach for these tools to explain the surfaces to visitors. However, I note these tools demonstrate discrete surfaces, not the complex relationships between multiple surfaces as designed by Gaudí for The Sagrada Familia church.

During my first field trip to Barcelona, Jordi Fauli from The Sagrada Familia’s Technical Office took me south of Barcelona to visit the Colonia Güell, Gaudí’s partially finished church
designed for the township of Santa Colonia de Cervello. Colonia Güell was to be the church at a planned workers’ colony for the textile factories of the Güell family, Gaudí’s long-time patrons (Tomlow 1989).

Figure 6.01 Site visit to the church at Colonia Güell.

Construction of the Colònia Güell ran between 1908 and 1916. During an extended design period, for almost a decade prior to the first stone being laid in 1908, it was here Gaudí developed the famous funicular hanging model he used to arrive at the unique solution for the church. Although only the crypt for the church was completed, the derivation of form and the synthesis of structure and model are unmistakably evident and the church is considered by many to be Gaudi’s greatest work and prototypical of The Sagrada Familia. (Collins, George R. 1970, p. 2: Burry 1993). ‘For Gaudi, form did not follow structure and construction. It was identical to them’ (Collins, George R. 1970, p. 9).

The basic tenet of the funicular hanging model was that by hanging cables from the locations of piers and columns, gravity would pull the form into shape. The cables, while hanging, were in tension and the theory was that, when the tension form was inverted, an identical form may be constructed in compression. This requires the material used in tension to be perfectly tensile and the subsequent material once inverted to be purely compressive. Thus Gaudí used cables for the model, and stone, brick and tile for the building.

Gaudí’s model was far more complex than an inverted structural model. The model was housed in a shed on the building site and scaled at 1:10. The cables were augmented by weights, small bags of lead, to indicate structural loads and these were scaled at 1:10,000. As I mentioned in Chapter Three, the funicular model owed a debt to graphical methods of
analysis and mathematical model making. The model was in fact a three-dimensional version of graphic statics; the lead weights represented structural loads and the cables the resultant forces. Both were intuitive methods, used by mathematicians and engineers to investigate increasingly ambitious concepts in their respective fields.

Figure 6.02 Hanging model of the Colonia Güell (Credit: Tomlow 2002).

The model, genius in itself, also serves to indicate the interesting and potentially illuminating developments in science and mathematics of the time. Mathematician’s models were generally constructed from string, plaster or wood and used as visual aids for instruction, while engineers, utilising graphic statics, were able to investigate forms not easily analysed before its introduction (Collins, George R. 1963, p. 72). Billington notes, with reference to the physical models the engineer Heinz Isler used to find form: ‘Isler found a method of physical analogies by which he could develop a scientific theory appropriate to structural art’, and ‘it is through these rules, learned ever more thoroughly as he plays, that the player discovers moves that he never before dreamed of’ (Billington 1983, p. 230).

For Gaudí, the combinatorial effect of these methods was the ability to affect variability in form through an empirical fusion of simultaneous representations, both geometrical and analytical. The funicular model provided a forum for mutually dependent cross-disciplinary collaboration.

Collins described the two-way interaction with the model: ‘If in making such a model we are dissatisfied for one reason or another with the forms which result, we can change the forms by shifting the weight ourselves and then correct the original calculations and the disposition of the loads in the building. It is essentially a tinkering machine’ (Collins, George R. 1970, p. 11)

As a tool for communication, it served to record a dialogue between Gaudí and his assistants who would, upon instruction, shift the lead about to vary the shape and, as it was located on site, it eventually served to convey construction information to the builders.
A reconstruction of Gaudí’s hanging model built for the Colonia Güell is to be found in The Sagrada Família’s museum and I visited this during my several research trips. The model is the PhD research work of Jos Tomlow and is documented in Das Modell (Tomlow 1989). Tomlow discovered that descriptive geometry was not suitable to represent the hanging model: ‘the model [the reconstructed one] gradually became the main tool to understand the original model form’ (Tomlow 2002, p. 45).

I began an interest in the Gaudí architect/engineer relationship, especially as it was conducted through a model. References to the extent of formal engineering at the Colonia Güell vary from the claim ‘there were no calculations involved’ (Beukers & Hinte 1999, p. 39) to Tomlow who quotes Bergos (Bergós Massó 1954): ‘Gaudi handed the so exhaustive work [meaning the work of the original model] over to the architect Jose Canaleta and the Alsatian engineer Eduardo Goertz, of the Compania de Aguas de Barcelona. The latter was a masterly mathematician whose services were used by Gaudi for his development of a method for quick structural evaluation.’ Casanelles (1967, p. 99) attributes Gaudí’s assistant Berenguer as someone who suggested that there were records of calculation sketches from the model.

I found reference to another of Gaudi’s assistants, Joan Rubio, both in The Sagrada Família museum ‘where he participated in... the calculations for the hanging model conceived by Gaudi’, and in the book Shaping Structures (Zalewski & Allen 1998). I wrote to Ed Allen, and also Professor Javier Monedero about this and deduced the following. One of the important distinctions in Spain is that it is architects who design the structure of buildings. They are trained as architects but specialise in building structure. Civil engineers, trained separately, engage in road design and the like.

At this time I had read John James’ account of the construction of the Chartres Cathedral. I note the references to tools: ‘See how simple the tools were. There is a string, a rule, a square or right angle, compass and proportional dividers. What more? Everything can be constructed from them alone. And this will be so with all the geometry found in the cathedral. The masters seldom used really complex figures, so the setting out and cutting of the templates could be kept as simple as possible’ (James 1982, p. 40). In this vein, I studied Robert Mark’s Experiments in Gothic Structure (Mark 1982). Both Mark’s and James’ research are forensic. James reconstructs the order in which Chartres was constructed and identifies the various building campaigns. Mark, on the other hand, sought to determine whether the Gothic structure had actually behaved as intended and developed a method for analysis of the stresses placed on various churches, particularly with regard to buttresses.

As I mentioned in Chapter Four, I was particularly struck by a reference by Robert Mark to the French Beaux Arts Professor Julien Guadet (1834-1908). Mark had included an image of a study for the French Gothic church of St Ouen in Rouen (Figure 4.02). Guadet’s combination of the French Gothic and classicist traditions led him to produce an alternative proposition for the church of St. Ouen. In a traverse section of one side of the nave he showed the flying buttresses of the original church replaced with a parabolic structure. Guadet arrived at this
scheme through the application of graphical methods of analysis. The proposal was published in Guadet’s collection of lectures – *Elements et theorie de l’architecture* (1902)¹ – a highly influential textbook past the mid 20th century. It is possible Gaudí, who exhibited in Paris in 1910, could have been introduced to the work there, if not previously in Spain.

I wrote to Robert Mark, asking whether he could add to what might have persuaded Guadet to pursue such a hypothesis, and for his thoughts on the extent of influence Guadet may have had on Gaudí. Professor Mark replied with the following two points he though may be helpful.

‘The first is that to my knowledge Guadet was enormously influential as a teacher both in his own times and (much) later. Peter Collins, who first brought the graphical analysis of St. Ouen to my attention, told me Gaudet was assigned to Beaux Arts students right up to the “revolution” of 69! It seems not at all unlikely that Gaudí knew of the St. Ouen analysis and was influenced by it. Second, the development of graphical structural analysis in the second half of the 19th century (largely introduced by Culmann, 1821-1881) produced a level of enthusiasm among practitioners (for being able to solve structures not easily treated before its introduction) not unlike late-20th-century finite-element modeling. Even my own structural studies during the late 40s included a goodly segment on graphical analysis. Architects of Gaudi’s time seem to have greater familiarity with the technology of structure than today’s; hence, even if he didn’t know Guadet, Gaudi could very well have been affected by this enthusiasm.’

During my research I have not been able to find another reference between the work of Gaudí and the proposal by the Julian Guadet for the church of St. Ouen. The effect Guadet achieved in removing the large mass of the buttress would have made most visual impact on the exterior of the church, affecting the light transmitted to the interior but without discernable influence over the interior of the building.

The beauty of the hyperbolic paraboloid surface much favoured by Gaudí is twofold: defined by its sets of ruling lines which are retained when the surface is adjusted, and that parabolas are to be found in the resultant curves, as the name implies – it is also one parabola swept against another. Unlike Gaudí, Guadet did not propose new surfaces to cloak the structure with – the side aisle, for example, continued to be formed with a pointed arch.

The hyperbolic paraboloid is well suited to being stretched around a parabolic or even a catenary arch, and in doing so exhibits a mutualism between structure and surface. While not extending to a fundamental interdependency, the relationship between surface and structure parallels the work of the architect and engineer.

It is not clear whether a funicular model was ever used at The Sagrada Familia. There are no contemporary references to one, and as the structure follows bay to bay, there is a repetition more easily quantified than at the Colònia Güell. Tomlow did not uncover any direct influences for the use of a hanging model, and Collins earlier had also not been able to do so².
Of great influence to Gaudí was the work of the French architect, Eugene-Emmanuel Viollet-le-Duc (1814-1879). It is known Gaudí returned a book he had borrowed by the architect (the Dictionary of French Architecture from 11th to 16th Century), much thumbed and notated. Viollet-le-Duc, as a historian and theorist, was influential at the time for his restoration work and Gaudí may well have been influenced by his structural rationalism. A connection can be made with arboreal analogy to Gaudí’s inclined structure, particularly the columns of the nave and crossing, which literally branch off from ellipsoidal knots to support the upper structure. I note here the similarities in their arguments.

Viollet’s argument in Entretiens sur l’architecture (Discourses on Architecture) is this:

Since every part of a building or construction must have its raison d’etre, we are unconsciously aware of every form which explains its function, just as we respond to the sight of a beautiful tree in which all the parts from the roots which grip the earth to the very last branches which seem to seek out air and light, indicate so clearly the factors which create and sustain these great organisms (Viollet-le-Duc, Eugene-Emmanuel 1863, p. 332).

And Gaudí is subsequently quoted

“Would you like to know what my model has been?” Pointing to a eucalyptus tree in front of his studio, Gaudí answered his own question: “A straight-standing tree; it supports its branches and these the twigs, and these the leaves. And everything grows harmoniously, grandly, since God Himself is the artist who created it. The tree does not need external support. Everything in it is balanced in itself. Everything is in equilibrium.” (Collins, George R 1977, p. 11).

Nevertheless there seemed to be congruence between the interactive hanging model as a collaborative tool between engineers and architects and I speculated as to whether I could replicate this environment digitally with parametric model of the Corbertes I was preparing. As it happened, it was not to be Corbertes, but the case study for the Parametric Bridge (II) that presented the opportunity to test this theory in my research.

The parametric model as space for collaboration

At this time I was preparing to present the Parametric Bridge (I) model to Arup in London. The schema for this project, discussed in Chapter Five, had been founded on fabrication information elicited through the tender process which was based on bending three steel tubes (two side tubes and a main tube) in two directions to achieve the three-dimensional form of the bridge’s tray. The aim of the research for that stage was to investigate this process with a parametric model, so that in close to real time, iterations of the bridge could be generated, thereby realising a design space that using explicit modelling would have been rendered opaque and unexplored.

The parametric model did indeed expand the design space, and I could iterate through it in
sync with the syntax of the problem structure of the project – the fabrication of complex
generation. Although I made a full parametric model of the bridge, I report here on the tests
I made to compare the parametric design for the bridge’s tray. Three variations of the form
are shown in Figure 6.03. Areas generated as a result of the main and side tubes are coloured
pink. The plate steel surface connecting the tubes is yellow. I made area calculations of the
different segments so if, when determining the form, costs were to vary greatly between using
tube or plate, then proportions of area could be used to constrain the model.

![Figure 6.03 Variations – 500mm/1500mm/1750mm radius main tube (L to R).](image)

However the schema driving the design space inherently limited the model to adhering closely
to the original geometry, rather than considering new possibilities. In my preliminary report
submitted prior to the Arup presentation, I proposed a continuation of the research along the
lines of my investigations into what was forming in my mind at the time, a digital metaphor
for Gaudí’s funicular model.

The CATIA software I had been using for my Sagrada Família research included a series
of discipline specific ‘workbenches’ including finite element analysis and an optimising
function. I saw in Robert Mark’s comment on the connection between graphical statics and
finite element modelling, an opportunity to replicate the collaboration between architects and
engineers as Gaudí’s funicular hanging model had successfully done. I speculated whether it
could act as a metaphor for a collaborative digital space.

In finite element analysis, complex geometries are divided into small elements defined by
geometric nodes that can be described mechanically by analytical equations. The equations
are linked together in large matrices computationally, in order to describe the behaviour of the
complete form. Used for many years in the aerospace industry, through the ongoing supply of ever more powerful computing, finite element analysis has migrated to engineering desktops. At present it is not commonly used in building design, as building structures still tend to be broken down into two-dimensional planes where elements or sub-assemblies can have the rules of statics applied. However, with more complex building forms, finite element methods become a critical tool for locating the stress concentrations.

While Arup considered my request, back in Melbourne I took the ideas to Dr. Neil McLachlan, a scientist with an interest in sound and music, and then also located in the School of Architecture and Design at RMIT University. Dr. McLachlan had been using finite element methods of analysis to predict the sonic behaviour of bells and gongs by optimising design parameters to vary their structural forms (McLachlan, Hasell & Keramati Nigjeh 2003). We began a series of experiments to test whether we could, in a single model, geometrically define a simple object, perform a structural analysis of it and then optimise the shape by varying geometric parameters. The idea being we could first explore a parametrically defined design space and then search for a solution within that design space.

These experiments were partially successful. We eventually performed the first task, but the second – successfully using the optimisation algorithm within CATIA to vary the shape parameters towards a structural goal – eluded us.

I reviewed some of the history of graphical methods of analysis from its roots in the 17th century, and we wrote a paper speculating on the possibilities of a single model that offered disciplinary views to its design space (Maher, A, McLachlan & Burry 2002).

The benefit of these experiments was that it offered good preparation when I received Arup’s approval in February 2003 to continue the research project for the Parametric Bridge.

The Parametric Bridge (II)

In March 2003, I visited Arup in London for two weeks to expand the project to consider finite element analysis and optimisation of the parametric model.

I was assigned Jan-Peter Koppitz, an engineer from Arup’s London Group Four, to work with me to establish a structural engineering view of the bridge’s parametric model. Our collaborative process extended to passing a laptop between engineer and architect, while sketching and writing ideas to convey each other’s principles as the views to the model were toggled between analyses and geometry, and of the design space.

One confusing situation arose when it was discovered that Arup’s in-house structural analysis software is called GSA (General Structural Analysis), an identical acronym to CATIA’s (Generative Structural Analysis). For this reason I refer to ‘Arup GSA’ and ‘CATIA GSA’ so as to distinguish between the two. Comparative results using finite element meshing and analysis require different methods to conventional structural engineering analysis and our close proximity to Arup’s Research and Development division was fortunate for detailed
discussions. After a week of work, a one-dimensional beam (stick meshing), two-dimensional surface mesh, and three-dimensional volumetric mesh were used to first corroborate the results between both ARUP GSA and CATIA GSA.

For the purposes of the research, the tray and deck of the bridge were determined to be an acceptable approximation of the form for the structural analysis. The bridge’s cable restraints were later added. A two-dimensional surface mesh was generated on the parametric model and a finite element analysis performed to determine the bridge’s displacement and stress. Through the discipline specific view of the structural engineer, this operation involved the addition to the project of local axes and restraints at the ends of the bridge, linear loads, and the application of material qualities including thickness (Figure 6.04). A routine of meshing the parametric model and computing the result of the analysis in CATIA GSA then followed any modification of the bridge’s design geometry.

Through the internal optimising algorithm within CATIA, parameters can be optimised to an assigned target value, be it minimum, maximum or a target value. Free parameters are then offered for variation and steps and ranges can be set. Two algorithms are used by CATIA: a localised Gradient ‘hill climbing’ method or Simulated Annealing, which adds in some randomness to offer the potential to ‘jump’ the hills and further search a design space.

At this point I had to reconsider the flexibility of the design space. As I described in Chapter Five, the parametric model had been limited by the design curves that I had extracted from the original Arup model, which were explicit and therefore without parametric variability. As I have shown, iterating through the free parameters in the geometric model of the bridge’s tray related to tube sizes, so it was with considerable effort that I edited and modified the database of the parametric model, thus increasing the potential design space. In seeking to extend the boundaries of the form and increase the parameters which affected it, the parametric model was redesigned so the guiding curve for the main tube, the underside of the bridge, was defined by a combined curve (Figure 6.05). This process was also informed through reviewing the strategy for the parametric design with the architects for the bridge, Future Systems, and in doing so gave more control to the form of the bridge. A vertical parameter determined the depth of the bridge and when added with a horizontal parameter, the combined curve relaxed the position of the model in space. Replacing the explicit curve with the parametric curve within the parametric database was time consuming and was at the limits of redefining the
hierarchical parametric design of the geometry.

**Figure 6.05** A combined curve (middle) is the result of the intersection of the extrusion of two curves.

To test whether we could search the design space, several scenarios were then designed for optimisation (Figures 6.06 and 6.07 show images from one scenario). Every iteration during optimisation requires the consistency of the parametric model’s database. In the bridge’s case, this consistency was still the adherence to its fabrication constraints. Each iteration of the model outputted, therefore, constituted steel tubes deformed in two directions with bi-tangential sides of ruled surfaces. The values of each parameter used in the optimisation routine were recorded at each change in a spreadsheet (Table 6.1. provides an example), and each iteration could be interpreted at a later stage, and then selectively revisited if so desired, by simply resetting the parameters.

**Table 6.01** Example of changing parametric values during optimisation.

<table>
<thead>
<tr>
<th>Iteration</th>
<th>Maximum Displacement (mm)</th>
<th>Cable Restraint Location (mm)</th>
<th>Tube Vertical Location (mm)</th>
<th>Tube Horizontal Location (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>23.4008</td>
<td>23.4008</td>
<td>12798</td>
<td>1484.59</td>
<td>5745.23</td>
</tr>
<tr>
<td>23.4008</td>
<td>23.4008</td>
<td>12614.6</td>
<td>1403.54</td>
<td>5708.67</td>
</tr>
<tr>
<td>23.4008</td>
<td>23.4008</td>
<td>14385.8</td>
<td>1466.18</td>
<td>5739.07</td>
</tr>
<tr>
<td>23.4008</td>
<td>23.4008</td>
<td>13228.7</td>
<td>1538.32</td>
<td>5787.56</td>
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<tr>
<td>23.4008</td>
<td>23.4008</td>
<td>12449.3</td>
<td>1441.57</td>
<td>5775.39</td>
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<tr>
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<td>23.4008</td>
<td>11784.1</td>
<td>1507.41</td>
<td>5824.81</td>
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<tr>
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<td>23.4008</td>
<td>12797.7</td>
<td>1484.57</td>
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<td>23.4008</td>
<td>12141</td>
<td>1545.82</td>
<td>5645.9</td>
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<tr>
<td>23.4008</td>
<td>23.4008</td>
<td>10935.1</td>
<td>1515.71</td>
<td>5744.4</td>
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<td>1482.43</td>
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<td>1484.57</td>
<td>5745.01</td>
</tr>
<tr>
<td>24.1539</td>
<td>24.1539</td>
<td>13318.8</td>
<td>1482.65</td>
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</tr>
<tr>
<td>24.1539</td>
<td>24.1539</td>
<td>12567.7</td>
<td>1439.34</td>
<td>5741.03</td>
</tr>
</tbody>
</table>

We used the displacement analysis results generated from CATIA GSA as targets for the
constraint solving optimisation routines, in effect using the engineering analysis to visually optimise the form. The process, when understanding the scope of what might influence a model’s geometry and its potential design space, became increasingly important in a collaborative sense to those taking part in the mediation of the artefact.

With the position of the combined curve parameterised, the bridge’s tray was optimised to minimise displacement. This optimisation generated a distinctly different shape, thinning at one end and then swallowing to a much deeper form than the original. The analysis view of the model is shown in Figure 6.06, and the geometrical view is shown in Figure 6.07.

Figure 6.06  Bridge optimisation (Curve Depth) analysis view.

Figure 6.07  Bridge optimisation (Curve Depth) geometry view.

Structural analysis of the bridge was able to be performed on the digital design model – an example of the single parametric model concept I had set out to test. The design model was optimised iteratively to structural targets by updating geometric design parameters while adhering to the fabrication constraints – the scenarios, both parametric and finite element, were computationally intensive, and each took approximately seven hours to run.
The research involved considerable technology transfer, adopting methods from outside the field of architecture and engineering and developing new techniques in each discipline. However, as the outcome of the research could be considered greater than the input of each contributor, therefore it could be said that a truly collaborative process has been undertaken. Further optimisation studies with parameters in the model were made during the research project and these are described in the paper (Maher, Andrew & Burry 2003), found in Appendix A.

6.2 The Sagrada Familia

The Parametric Bridge (II) project was a lesson learnt in technology and collaboration from The Sagrada Familia church and something I did not replicate on the research project for the Corbertes. Instead, I took the lessons from the Parametric Bridge to testing the boundaries of a parametrically defined design space for the internal surface of the Corbertes. This I did through searching the design space.

When designing the parametric model for the Corbertes I pondered the composition of the interior of the roof. I had not received instruction from the Technical Office as to the design intent and two options presented themselves. One option is an interior of equal thickness. The other option is an interior composed of ruled surfaces, similar to that of the exterior. The difference is that the hyperbolic paraboloid surface, being composed of parabolas – one parabola swept against another – is a quadratic form. This means, as parabolas do not scale in an equidistant manner, a form composed of ruled surfaces on the inside and outside cannot have a uniform thickness.

This is not an issue that arises often at The Sagrada Familia as many elements composed of ruled surfaces surround a solid form. Such surfaces are inscribed on the exterior of a solid form. However, for the Corbertes, both interior and exterior would be visually evident as they are also internal spaces. When I talked with Jordi Fauli of the Technical Office about this he said the most likely outcome was that formwork would be made for the Corbertes and poured to a uniform thickness.
I believe that visual evidence from the original plaster model suggests that not only is the exterior of the roof composed of ruled surfaces, but also the interior. The exposed section of the model shown in Figure 6.09 clearly indicates a non-uniform relationship between the exterior and interior curves. Jordi Fauli suggested it would be a good investigation to test an interior of ruled surfaces and analyse the increase in material required to fill the form.
The benefits of using hyperbolic paraboloids for both external and internal guiding surfaces of the Corbertes are that the intersections between the interior surfaces adhering to Gaudi’s codex will be along straight lines and the openings on the external ruled surfaces that connect through to the interior will also lie on lines of ruling.

I set about designing the parametric model for the interior of the Corbertes with ruled surfaces. Referring back to Figure 5.09 in Chapter Five, there are a number of external positioning constraints. For example, the hyperbolic paraboloid surface HP3 meets the adjacent internal planar surface at a floor level, as well as the lower point of hyperbolic paraboloid surface HP2. Figure 6.10 shows the geometry model and the points and planes involved in the design of the internal surface.
I then used the optimisation algorithms I had employed on the Parametric Bridge (II) to search the design space by moving the free parameters of the interior surfaces to find a minimum thickness required for construction. I graphically documented the structure of the parametric model (Figure 6.11) for this investigation. This diagram is for the interior surface HP1 and begins at a high level with the top most virtual point (VP in Fig 5.09) for the Corbertes. I have identified the geometrical moves which can be related to Figure 6.10 and I show where the optimisation algorithm operates.
Figure 6.11 Process diagram for searching the parametric definition of HP01 (interior).
Figure 6.12 shows the distribution of thickness, once optimised, between the interior and exterior, both visually and graphically. The long tail of the distribution of thickness shows that, in the case of HP1, for a given thickness a figure close to the minimum could be achieved for more than 70 per cent of the surface, while the maximum thickness increases considerably. These results were submitted to the Technical Office.

Figure 6.12 Distance analysis between interior and exterior hyperbolic paraboloid surfaces. (Visual above and by graph below). Minimum thickness this case is 310mm.
Both the Parametric Bridge and the Corbertes parametric models were designed in dedicated parametric modelling software (CATIA V5) where the data structure is preserved and editable. As I identified in Chapter Two, another way to parameterise geometry is through a generative procedure or series of procedures in which the data structure is held in software code and the process of executing algorithms creates instances of geometry.

In all the case studies, only Suspended Arc combined both methods. For Suspended Arc I developed a parametric model that could be adjusted to fit the sculpture within the existing site conditions as they were identified through surveys. The model was also updated to reflect variable clearances above a roadway that appeared to change whenever a new authority was consulted. I first defined the base geometry in the parametric modelling software CATIA V5. However, when certain elements, such as the cables in the artwork, needed to be completely redefined on a regular basis I found a more effective method was to write software code using CATIA’s implementation of Microsoft’s Visual Basic for Applications (VBA). Therefore, Suspended Arc was a hybrid case – both an editable database preserved from a construction history and a generative process procedurally modified through software code.

An editable or procedurally modifiable design space has congruence with Daniel Herbert’s (1993) specifications for designing electronic systems for architectural design after his investigation into the role of study drawings. Herbert found that study drawings were used for active participation in formulating the design, not just recording it. He proposed that ‘CADD systems, like study drawings, should be engaged as artifacts with their own open structure that can be modified either by chance or by deliberate strategies’ (Herbert 1993, p. 119). The last part of this section describes the design space for the Docklands Tubes in which the geometry was created through a generative process.

The algorithms developed for the Docklands Tubes (described in Chapter Five) were designed to decompose free form three-dimensional curves to a series of tangential arc curves. They were designed to suit a fabrication and assembly process, and each time an algorithm ran eight parameters could be varied for each curve. These parameters included the minimum arc length and radius, and the maximum curvature change.

Three people – me and two students – became practiced in the art of applying the algorithm and the boundaries of the design space that had been parameterised. Because a curve is continuously changing in radius, whereas an arc is of fixed radius, the algorithm ‘steps’ through curvature changes and the result is always an approximation. As we ran it for each curve of each sculpture, we sought to balance the result between using a greater number of smaller arcs for a very close approximation to the free form curve and longer arcs with fewer joints. Longer arcs meant less labour in fabrication and assembly, and a more economical budget.
An amount of tacit knowledge was developed in this technique when testing and applying the procedure and reconciling the physical design (the free form curves) with its expression in arcs. Figure 6.13 give an indication of the resultant designs that were produced as the parameters were varied for each run.

The process of applying three-dimensional design development to a complex form instigated a reappraisal of the design, recalling the artists’ preference for a ‘seamless yet not smooth’ aesthetic, and offered a view to the use of the parametric model as a design tool.

**6.3 Pseudocode as a tool of communication**

Drawings, particularly sketches and diagrams, are powerful intuitive methods of interaction, yet conventional software does not embrace their richness in representation (Evans 1995). The lineage of this situation exposes the schism of digital media where translation occurs through the framework encoded in the two-dimensional drawing conventions of separate disciplines. In fact Voyatzaki and Williams, in their study of the design of non-conventional building structures, noted the cyclic nature of collaboration between architects and engineers.
was disrupted by the inadequacy of conventional drawing techniques to describe difficult geometry; either by hand or computer (Voyatzaki & Williams 1996). The intuition and tacit knowledge brought to each project, embodied in disciplinary practice, remain beyond general algorithmic encapsulation.

Here again, Gaudí’s vision in working with non-standard forms is noted. Gaudí’s methods incrementally evolved with his buildings and projects throughout his lifetime, and generally eschewed orthogonal representation – drawings he usually reserved for official purposes. Today, the recrudescence of the curvilinear which is in part engendered through the use of the computer has increased the index of opportunity for alternative methods of interaction and representation.6

I have used the Docklands Tubes as a segue to the final section of this chapter. During my research investigating the traversing of the design space afforded by parametric models, I took particular interest not only in the conversations between allied disciplines such as architect and engineer, but also when computationally constructed spaces are designed between and architect and computer scientist.

Using generative procedures for case studies such as Docklands Tubes or Digital Stereotomy, I began to consider the development of the shared computational understanding of the design. The value in the practice-based research of these case study investigations was through the interaction between the two disciplines – architect and computer scientist – and the development through conversation towards explicit instruction in code. I would classify the conversation within the research as transdisciplinary, created from interdisciplinary interaction, but not being strictly of one discipline or the other (Zeisel 1984, p. 52) with the aim being ‘to transfer implicit design rules out of a designer’s head and into the code’ (Mitchell 2003, p. 76) – a method between two disciplinary understandings when more than one person is involved.

I made the diagram below during Space Division, Case Study Six. An important aspect in the research for an alternative version of the façade of the Beijing Olympic Pool was the constant communication between the computer scientist and me. Because of the difference in domain knowledge, both parties faced possible misinterpretation during the conversation and much worthwhile effort was expended explaining one’s own domain of terms and jargon.

Pseudocode is the description of an algorithm in natural language prior to its codification within a software language. This is the portion of design conversation conducted through our own form of pseudocoded narrative. We used the pseudocode as a repository for our jargon (expressed in the middle region of the diagram as the shared knowledge common to both of us).
Figure 6.14 Sharing disciplinary knowledge.

The sets of the diagram with solid boundaries contain disciplinary knowledge. This example for Space Division contains the architect’s and computer scientist’s sets. These sets can be thought of as the knowledge that is brought to a particular design space. As such we might consider the sets as dynamic with the ability to expand and contract on a project basis. The knowledge used for a project is represented by a third indistinct set (shown dotted).

I felt this diagram, which I drew as we worked, was important as it helped us understand the way we transferred information and decisions from a tacit to explicit state. It is where the semantics of a design space found its syntax within the grammar of a software language.

Communicating parametric generation

This research alternative version of the Beijing Olympic Pool was undertaken alongside the early stage design for the pool and the design team were using three-dimensional geometry based on the Weaire–Phelan structure, the most efficient foam structure (Kusner & Sullivan 1996). My research was something of a risk mitigation exercise for the designers, Arup. During a fast paced project, the firm posed the question: could a research team look at alternative methods of designing a random looking but repeatable façade loosely based on soap bubbles? The parametric design we developed together was decided after studying patterns and lattice structures. We opted for a voronoi tessellation (which divides space equidistantly between points in a plane). The aim of the Space Division case study was to develop a parametric design that generated a series of repeatable complex forms with few parametric inputs.
I do not describe the full process of generating the voronoi-based option here as the focus of this section is the space in which our two disciplines contribute to a shared view of the design space (Fig 6.15). I made the following diagram to explain the stages we developed as pseudocoded dialogue between architect and computer scientist. In the first stage, beginning with the external plane of the facade, a tessellation is developed and the vertices of the pattern are used to provide the points of interest about which voronoi cells are equally bound. This is where the parametric variability occurred, so several versions of tessellations could be tested.

Once the voronoi tessellation is calculated the system at this point is exposed to the question of contractor space. Elements within the cells are considered to be either steel members or nodes, and adjustments within the cells are made to suit some criteria. For this case study, it is either standardising the node design (defined by the angles of the voronoi cells’ vertices) or restricting the length of the elements. In either case the success rate of rejigging the voronoi cells to suit either is between 62 per cent and 67 per cent, or roughly two-thirds conform to some sort of standardisation.

The ideal in this regard is to achieve a defined number of nodes and lengths which could be repeated in numerous ways to achieve the irregular pattern. Part of the process of checking element lengths is to find lengths which are too small and to remove them. This is reversed and the element is extended, if by deletion this reduces the cell to four or less sides. This is the dialogue as a building system rather than pure geometry.

Rather than simply construct props between the inside and outside walls of the facades, patterns are also constructed three-dimensionally between about two planes with randomly occurring z values that are adjusted if they are considered too close to either inside, middle or outside.

These distances are then all measured and where the distance between nodes is considered too great, struts are inserted (Fig 6.15). In this way, a three-dimensional structure is generated which is continually adjusted to suit perceived constraints to build-ability.
6.4 Conclusion

This chapter considered parametric design in action and tested the early activity in the prefiguration of the design, established in the previous chapter, with the resultant design space. The research in this chapter most directly offers a ‘sense of usefulness’ of parametric design. I examined the potential to traverse a parametric model as a design space as well investigating opportunities to share the derived design space with other disciplines.

In a lesson learned from The Sagrada Família, I theorised the parametric model as a digital metaphor for the hanging model Gaudi’s developed for the form finding of the Colonia Güell.
church. After a series of experiments, I used the Parametric Bridge (II) case study to sponsor a research project to test the parametric model as a collaborative design space an engineer and architect could simultaneously inhabit.

I found two disciplinary views could be established of the Parametric Bridge (II)’s parametric model. The engineer’s view permitted the establishment of constraints to delimit the space for loading conditions and the architect’s view similarly offered a view of the geometry. Once effected, the parametric model responded to both disciplines’ desires and the space could be explored interactively.

With an optimisation algorithm enacted, and continuing to adhere to the declared constraints of both disciplines, a design space was revealed that supported two different activities. They could not only be explored but also searched in a directed manner. Throughout the experiments, the assumptions made when designing the design, were returned to when the boundaries of a design space were reached. An open and editable parametric model is required to revise early assumptions when further information is known.

The work involved considerable technology transfer, adopting methods from outside the fields of architecture and engineering and challenging established techniques in each discipline. As the outcome of the Parametric Model (II) could be considered greater than the input of each contributor, it could be said to be a truly collaborative process. In the Parametric Bridge I did find a digital space congruent with Gaudi’s hanging model in which it was possible to firstly explore and then to search collaboratively. I identified these multimodal views of shared and mutable design spaces as transdisciplinary, enabled through cross-disciplinary interaction but not entirely of one discipline or the other.

In my case studies, psuedocoding was used between architect and computer scientist in the absence of systems for notation for design communication. This at best augments the design process, and while serving to perpetuate connectedness, in doing so reinforces the absence of communication tools that support the heterogeneity of complex process that inform the act of designing.
Endnotes


5 I presented Parametric Bridge research to Dr Kristy Shea at Arup in March 2003 who told me that Finite Element methods were originally developed for buildings.

6 Architects and engineers drawings have historically varied being dependant on skill, compositional order and the development of drawing instruments. See Hambly, M 1988, Drawing instruments, 1580-1980, Sotheby’s Publications, London.
Chapter Seven  Parametric design and production

Introduction
This final chapter of my research concentrates on the output when designing parametrically. Chapter Five described the building of the schema, the pre-investigative work that must go into defining a parametric model. Chapter Six described the opportunities that lie in working with a parametric model as the design space afforded by the model is traversed.

The aim of this chapter is to examine the output of the research work and its relationship to research in the broader realm of the construction sector.

To communicate this, the chapter is divided in three sections. Section 7.1 describes the methods employed to capture existing information from the site of The Sagrada Familia church. Section 7.2 focuses on the question posed in the ARC grant on the various connections between old and new, and the flexibility of the parametric model. Finally, Section 7.3 asks what some of the factors are when adopting parametric design to construction. It does this with reference to the particular output of one case study.

Case studies used in this chapter
I concentrate on two case studies in this chapter; the Corbertes at The Sagrada Familia and the Docklands Tubes. This chapter focuses heavily on the investigations for the ARC grant and the Corbertes case study. It addresses measurement for the parametric model at building scale. I then provide two examples of the flexibility when varying the parametric model to conditions found on site. The Docklands Tubes are used to demonstrate an alternative form of output that raised questions for architectural praxis more generally.

7.1 Measurement at full scale
This section describes the work in my research most closely associated with the aim of the ARC grant upon which the research is founded. As introduced in Chapter Three, it was to extend research at The Sagrada Familia to test the flexibility of a parametrically defined model with the assumptions that are made where accurate measurement is not possible. The work was to be centred on examining the connection between that based on Gaudí’s codex of ruled surfaces and the fabric of the existing building. The original subject of the research was to find a connection between the transept roof, as defined by the parametric model of the Corbertes, and the Nativity Façade at The Sagrada Familia church. The new onto old (referring to the grant’s title) in this case was both literal and metaphoric, as the connection is between the earliest work on the site (finished at the turn of the 20th century) and Gaudí’s mature work of some 20 years later – as found in the plaster Corbertes model.

I made Figure 5.01 in Chapter Five to show the complex relationship that emerged between different scales of old (plaster model) and new (digital model) to the old (site conditions). In Chapter Five I introduced the concept of three-dimensional measurement at differing
scales, from digitally scanning Gaudi’s Corbertes model to gathering information on site in Barcelona. The first two sections of this chapter are dedicated to the completion of that task.

The premise of the research is one that should be familiar to many architects when working with existing structures. That is, what contingencies are to be made for what is not known, and how might they be undertaken and compensated for? The proposition in the ARC grant was that the precision promoted by the use of the computer was in opposition with the ‘loose knowledge’ implicit within existing structures.

A common method of anticipating the unexpected in construction is the use of financial contingencies that are carried within project budgets to allow for what is not known, what cannot be known, or to hedge against assumptions made in the earlier stages of design as a project unfolds. These situations occur ordinarily before demolition has removed obscuring structure, or when there is restricted access to a site, or inaccessibility to a portion of a structure (RAIA 2005).

The transept roof at The Sagrada Familia was selected for the research because there is no surviving evidence that a resolution for the roof connection with either transept façade (being the Nativity and Passion facades) was made during Gaudi’s lifetime (Burry & Datta 2001). The ARC grant stipulated the Nativity Façade for research, but during the project the Technical Office requested the opposite connection, between the Passion Façade and transept roof be investigated. The reason was that this connection was much closer in the construction schedule and posed a more immediate problem.

The genesis for this research, focussing on methods of three-dimensional measurement as a link between the new and the old, began during my first site visit to The Sagrada Familia when, amid the ongoing construction activity, direct access was not available to the interior of the Nativity Façade. This arose as the façade was partially obscured with the levels of temporary scaffolding and construction platforms.
Prior to my site visits, detailed surveys for the existing Passion Façade (not at the point of connection with the transept roof, however) and the Apse had been carried out by the Topography department of the Universitat Politècnica de Catalunya (UPC). With further survey work not imminently scheduled, an intermediate position was sought to give three-dimensional geometrical definition to the built structure, and an externality for the parametric model.

In all, five projects were undertaken with the common theme of measurement at full scale to aid the modelling process and to link the parametric design. Two of the projects, connecting the Corbertes module to the transept facades (Passion and Nativity) will be described further. The research for the Nativity Façade was undertaken in sub-sections differentiated at different times of collection and processing. This project spanned the entire research period, including two specific measuring field trips. The other projects were speculative, extending the techniques I was testing. Of these projects, two related to the exterior of the Passion Façade and that façade’s single source – a photograph of a drawing. The fifth project also investigated historical photographs as a source of measurement for the unbuilt main façade; the Glory façade.

My progress paper, in the Appendix, entitled Hybridized measurement: Interpreting historical images of Sagrada Familia Church in Barcelona using CAD-based digital photogrammetry, details the Passion and Glory Façade experiments (Maher & Burry 2002).
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New to old at The Sagrada Familia

Gaudí’s lasting legacy has been greatly enhanced by the decision to build a vertical section of The Sagrada Familia first rather than the entire church layer by layer. Why The Sagrada Familia was built bay by bay rather than in horizontal layers is not clear. John James’ study of the construction of Chartres cathedral refuted a view James claimed was commonly held: that cathedrals had always been built in vertical sections, bay by bay (James 1982, p. 21). The answer in the case of The Sagrada Familia may well be political, as suggested by Martinell, where the Nativity Façade was financed by a large donation which Gaudí was encouraged to spend expeditiously to avoid any possible expropriation by the bishop of Barcelona (Martinell 1975, p. 290).

Having the Nativity Façade and completed towers of the eastern transept has had the effect of a permanent billboard over the years, promising what could follow on the site. At the time of construction it was no doubt more convincing to have a vertical portion of the church presented to a public upon whose donations were depended. For the architect it has ensured his built vision, from crypt to tower pinnacle, has forever dominated the continuing construction.

As noted earlier in my research, Gaudí’s white plaster models can be considered the base geometry of his proposals, where information such as the polychromatic finishes of surfaces Gaudí employed elsewhere is absent. Had Gaudí spent his time working from the footings of the church in a layered manner around its entire perimeter, one can imagine his influence would have been lessened without the densely built liturgical treatment of the Nativity façade, the bell towers or their cubist pinnacles as a kind of final twist in the geometry (Fig 3.03).

Indeed any controversy stirred by the continuing construction is inextricably linked to authorship. In this regard Gaudí now shares more with the signature designers of the present that with the cathedral builders of yore. The public discussion about the continuing construction began at the time of the construction committee’s reorganisation in the 1950s with a forum organised in 1959 by the Centro de Estudios Gaudinistas (Centre of Gaudinist studies, an association founded in 1956 by César Martinell) to discuss how the venture for which ‘the end is not even a glimmer on the horizon’ might be progressed (Martinell 1975, p. 450).¹ In any way that work progresses, connections new to old have to be made and can also be found in evidence on site. The first were presented to Gaudí during his own lifetime.

The preceding work of The Sagrada Familia’s original architect del Villar determined much of the site orientation for the church, and while this may have caused some frustration, following in another’s footsteps was not unique in Gaudí’s career. The commission for another project, the College of the Teresians, was awarded to Gaudí with construction already underway (Van Hensbergen 2001, p. 105).

The consequence of building vertically, section by section, or bay by bay, is that ambiguity is drawn primarily between the elements on the vertical connections. The inverse occurs with a layered approach. James demonstrated Chartres Cathedral, built in horizontal layers, displays
joints where logical interruptions were required, such as the springing point of an arch prior to formwork erection. Work then continued in subsequent construction campaigns taking the building higher. James describes a church of variant detail; the results of the vagaries of accepted measures and simple tools used to set out and template the building, but which nevertheless cohered to boast a uniform interior (James 1982, pp. 21-41).

Gaudí had first worked on the crypt and then the apse. The work of that decade 1883-1893 remained in the Gothic revival style laid forth by del Villar, only with indications through some elements (such as the shell forms of the gargoyles or the vegetative ornamentation atop of the apse spires) of the forms that were to come.

The Nativity Façade began in 1891, and is emblematic of the church’s transformation to Gaudí’s deeply liturgical and highly mannered form. Although it is the exterior that is so well known, I found the interior, bare by comparison, fascinating (Fig 7.01). Here the stonework stands awaiting further carving and statuary upon its empty pedestals, in striking contrast to the exterior that is covered with decorative finishes. Gaudí daubed the façade first with plaster during construction and gradually replaced the elements with stone (Burry 1993). As a facade, with the emphasis on its external appearance, it offers a unique view of the transformation from its underlying neo-Gothic structure.

Figure 7.02 A panorama between the two transepts, from the Passion Façade (L) to the Nativity Façade (R).

The Nativity Façade was completed in 1900, and although the final work on the exterior was ultimately finished by Gaudí’s assistants after his death, it predates Gaudí’s use of ruled surfaces. Construction had drawn to a halt with the lack of funds by 1914. With the site at a standstill, and having been notified by the Güell family that the church at the Colònìa Güell would not continue, Gaudí began resolving The Sagrada Familia in its final arboreal form through the model making process.

Methods of measurement

I obtained an earlier experimental survey of the Nativity Façade by Clini and Fangi (1991), using non-conventional photogrammetry at The Sagrada Familia from the Technical Office during the case study. The research was of interest for a number of reasons. The nature of the experimentation predates digital photogrammetry but anticipates its processes. The measurement in the research was undertaken with non-metric cameras and used the control points for editing graphically within a CAD program. The research also used the interior of the Nativity Façade and the finial of St. Baranabas atop the bell tower. They observed that the broader use of non-conventional photogrammetry in architecture required a shift in the skill
base akin to the spatial skills of architects, and this demand was corroborated in my research.\textsuperscript{3} Clini and Fangi’s research produced the pinnacle above the façade as a three-dimensional form. The interior of the Nativity Façade, however, was plotted as a two-dimensional elevation. Researching this method of measurement, I found Bae et al (2002) presented work to code the design rules of traditional Korean buildings parametrically. The research applies dimensions found through measurements in photographs to values within a parametric model. In their research it is the measurements that are used rather than the acquired geometry.

In addition to employing these techniques for measurement and/or geometric reconstruction, Debevec (1996) presented a method for generating three-dimensional models with a complexity derived through an image based approach over relatively simple geometric models. A visual complexity is derived through much less modelling effort.

CAD-based digital photogrammetry refers to the integration of CAD and photogrammetry and part of the motivation for exploring CAD-based digital photogrammetry, as a technique for gathering three-dimensional data, was that its adaptation extended the use of tools already employed by the Technical Office at The Sagrada Familia: laser measurement and digital photography. I found prescient comments in relation to the method of measurement I tested. ‘From one side the operator could be rather inexpert in photogrammetry but from the other side he should have a deeper knowledge in architecture’ (Clini & Fangi 1991, p. 175).

I envisaged the results of the research may both serve to broaden the use of such tools and skills on site, and act as an intermediate source of spatial data between the more complete and accurate surveys of the UPC. Although such methods lie beyond the site measurement skills of most architects, this hypothesis was able to be tested when two research assistants from MIT attended the site, untrained in photogrammetry. I sent tools and software from Melbourne to Barcelona and then, with instruction and through remote management, several projects were completed within a few weeks.

Digital photogrammetry uses software to make measurements from images, and is available in comparatively low cost commercial packages. The interdisciplinary combination of the fields of computer vision and photogrammetry has served to enlarge the scope of data acquisition and processing architects are able to deploy on a project, by making generally available the ability to generate three-dimensional information through processing multiple two dimensional images. Accurate modelling can be accomplished without expensive recording equipment or analytical plotters. I found it to be analogous to the paradigm shift from the two dimensional plane into three-dimensional space.

**Measuring the Nativity Façade – experiment one**

The recording of the section of the eastern transept at the Nativity Façade where the roof terminates extended throughout the entire length of the case study. The final result is the combination of work undertaken over different periods of time and with different tools. The hybrid nature of the project involved measuring the inaccessible location with hand-held laser
meters through to full scale three-dimensional laser scanning and digital photogrammetry. The time scale began with the first site visit in May 2001. This was followed in July 2002 by another effort which was managed remotely between Barcelona and Melbourne. Later, a laser scan of the eastern transept’s rose window (from the ground and below the scaffolding) was provided by the UPC. The intervening period was then largely devoted to the roof connection at the western transept, the Passion facade. In June 2004, the project was revived, to amalgamate the projects to a single reference.

The continuation of research in measurement for the Nativity Façade was pursued to form a three-dimensional model of the existing conditions, without direct access and prior to a survey, using non-conventional methods in a discipline specific way. With the New onto Old project changing focus to the Passion facade, the connection with the Nativity Façade remained un-bridged. Interestingly there will be very little to connect with, and the project may be able to use the connection found for the western transept as a schema for modifying surfaces to close the transept roof.

The first photogrammetry experiment, undertaken on the initial field trip at the beginning of this case study, was one of intense learning. Two problems were presented on this first visit. The scaffolding platform facing the Nativity Façade was at the 40 metre level and offered a rather constricted planar view of the facade. The second problem exposed a technology transfer issue, in this case the differing requirements between traditional terrestrial photogrammetry and digital photogrammetry.

The first project predated any determination of a software choice for digital photogrammetry and so an approach was sought from RMIT University’s Geospatial Sciences Department for the most successful image capture. Their advice was directed at classical stereoscopic photogrammetry where a pair of photographs is either made with a stereo-metric camera or with a conventional camera planar to the object, with some overlapping. In this case, three-dimensional points are recovered through a process of stereo plotting.

Digital photogrammetry, using software, converges two or more photographs, taken from a single viewpoint from different positions (monoscopic convergence). The closer to 90 degrees between the camera positions, the greater accuracy is achieved. The algorithmic process in monoscopic convergence photogrammetry, called the bundle adjustment algorithm, calculates the positions of a camera for each photograph and then the positions of co-located points within images, as more photographs are added. The planning requirements are thus fundamentally different from classical photogrammetry and photographs of the facade, that were not intended for the survey, were used instead.

The duration of this project was two days on site, two days learning the photogrammetry software, and then recovering geometry over a period of four days.
Some effort was spent taking several measurements with a hand-held laser device to establish control points for the project. These control points were used throughout the research. In addition, geometric constraints across the horizontal axis of the façade were easily identifiable, although this was not the case for horizontal axis in the other direction, or for the vertical direction.

**Measuring the Nativity Façade – experiment two**

With lessons learnt from the first experiment at gathering site information, the second experiment was undertaken in July 2002 with two research assistants from MIT on site. During the interval between the two measurement efforts further scaffolding had been built (Figure 7.04), providing limited access to the facade.
This project was managed remotely from Melbourne through email and online meetings. The camera from the first project was sent with the calibration files and photogrammetry software so that the recording and processing of the project could be undertaken simultaneously. In recognition of the ability of close range digital photogrammetry to measure and generate three-dimensional models, the Nativity Façade was one of a number of measurement projects over a six week period.

The assistants were charged with finding views with greatest perspective to the facade. Permission was sought to set up climbing ropes so that printed targets could be fixed to points of interest. The fragility of the mortar on the surface, exposed to the elements for over eighty years, limited access to the entire area.

One assistant set targets along a fixed line, and the other placed targets at as many points that could be safely reached. Visually identifiable targets served to clearly mark a point which can be especially useful when there are many similar surrounding points such as along the edge of the stairs or the brickwork in a planar face. This was observed when non-marked points were added to the processing. The bundle adjustment algorithm produced a very low error factor when the targets were used.

**Merging the work – hybridised measurement**

During 2002, the UPC were testing a terrestrial laser scanner, the full scale equivalent of the laser scans I employed on the models, to scan the rose window from the interior of the Nativity facade. They sent me this file as a collection of points (Figure 7.05). In the scan, the underside of the scaffolding is clearly evident which continued to obscure the upper section of the facade. This information was not used directly within the photogrammetry survey as control points as the information was spatially adjacent. By extracting edges from the scan...
this geometry did provide the extension to the measured arcs over the rose window and thereby validated the photogrammetric geometry.

**Figure 7.05** The interior of the Nativity Facade's rose window scanned with a terrestrial laser scanner.

To finalise the measurement project of the Nativity facade, the three projects, experiments one and two and the scan, were merged together to produce a three-dimensional model. The projects from the photogrammetry surveys were merged together and processed with the bundle adjustment algorithm. Control points used in common between the projects were used to reference one against the other and the overall geometry was improved.

**Figure 7.06** The hybridised measurement for the Nativity facade.
7.2 **New onto old – connections**

In this section, I describe the two projects that tested the flexibility of the parametric model when made congruent with information gathered from site. My proposals for the two transept façade connections are shown and I have included the skylights on the Corbertes as surveyed floor levels required a re-design of their openings.

**Corbertes connections**

It is the lack of documentary evidence, either drawings or models or reference in literature that inform the assumption of the Technical Office at The Sagrada Família church that no connection between the roof and the transept facades (or indeed the main façade) was proposed during Gaudí’s lifetime.

There is evidence that Gaudí had returned to the eastern transept connection after Nativity Façade had been built. In the archive of one of Gaudí’s assistants, Domenec Sugranyes, a photograph was found in 1997 showing a model at scale 1:25 of The Sagrada Família’s interior viewed towards the Nativity Façade. Although the Corbertes are absent, Bonet notes some elements without logical extension to the work of Gaudí’s final forms had been removed. This photograph has served to embolden the Technical Office to give consideration, as Gaudí may have, to removing elements of the church which no longer serve a purpose and thus make changes to the existing structure (Bonet i Armengol 2000).

Although there are no known proposals by Gaudí, the Technical Office produced a drawing in 1965 that can be regarded as the sum of knowledge to that point, showing a section through the church, including the central tower, roof and transepts.
Figure 7.07
I have enlarged the areas circled on the drawing above to show in detail some of the consideration given to the connections.

**Figure 7.08** Detail of 1965 drawing at section through The Sagrada Familia central tower and western transept. Showing the anticipated Corberes termination and roof connection with the Nativity facade.

Comparing the position of the top of the rose window of the Passion Façade – as built – to which the connection must be made, with the 1965 drawing, it is immediately clear that the connection will not be the connection proposed in the drawing.

A geometric digital model of the rose window at full size was provided by Professor Burry and the as-built location was provided by survey from the Technical Office at The Sagrada Familia. Following Figures 7.10-12 are proposals for the connection between the transept roof and both facades.
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Figure 7.10 Proposal for the guide surfaces at the Nativity Façade roof termination. (Projected onto the 1965 drawing – inset).

Populating the surfaces

Once I made the connection with the as-built information from site, the manner in which the end of the transept roof could accommodate the elements of the Corbertes was addressed. Figure 7.11 shows a collection of the elements on the end of the transept at the Passion facade. On the modified hyperbolic paraboloid HP2, a ruled surface opening is located in a similar position to that of the 1965 drawing. These elements are parametric instances of the openings found elsewhere. The common surface characteristics were used to identify the properties intrinsic to each. Although the same schema for an opening is employed, the lines of ruling on the modified HP2 surface differ from the other HP2s so the instance of the ruled opening varies to its kin elsewhere. It sits atop a large shield which offers a landing for a balcony.
I also used the extended planar face to fit another skylight, which follows the modified proportional values of the preceding skylight. These elements were offered for consideration by the Technical Office and to illustrate the flexibility of the parametric Corberte model.

Figure 7.11 Proposal for the Corbertes at the Passion Façade roof termination.

Figure 7.12 Proposal for the Corbertes at the Passion Façade roof termination. Projected onto the 1965 drawing.
Accommodating changes

Towards the completion of the model, the existing construction work was surveyed and the information sent for comparison with the model. This required some further refinement of the connection surfaces parameters and re-running of the thickness algorithms I devised and described in Chapter Six, for the internal surfaces, to match the as-built location of the rose window. These changes, too, were accommodated parametrically.

Varying the skylight openings

During the final stages of my research I received the surveyed floor levels for the two levels within the Corbertes by survey from the Technical Office. These levels proved a more rigorous test of the flexibility of the parametric model when accommodating the assumptions that had been made prior to accurate measurement.

I had known the base of the Corbertes was at the Relative Level (R.L.) 46.15m, and there is another floor above, evident in the Corbertes model. The surveyed position of R.L. 54.65m was sent to me for the top of the upper floor and the edge profile of the concrete slab, shown in red in Figure 7.13. On the left I have overlaid the position of the scanned model relative to the 46.15m level and immediately it is evident that the floor structure will obscure the skylight opening.
The planar surface on which the skylight openings are located is inclined towards the virtual point VP1, and I designed the parametric schema for the openings to ensure horizontal points remain horizontal if they were to move in position on the inclined slope. The measured floor levels introduced new constraints for locating the skylight openings in the planar surface. The constraints were to provide clearance for the openings under the floor structure (1 in the
diagram) at the R.L. 54.65 m level, and when moving the openings down, the intersection with the edge of the adjoining surface (2 in the diagram) provided a boundary to the skylight location.

On the right is a solution I found that satisfies the parametric schema, including the proportional system elicited from the original model. The method I used was to test the central guide at the apex of the surface and move the guiding geometry for the lower window to position (2). I then devised an algorithm within the parametric model to optimise the angle and set out the guiding geometry to satisfy the dimensions.

The solution on the right takes advantage of the planarity of the surface and rotates the openings about the surface to achieve a fit with positions 1 and 2, so as to maintain the widths of the openings as measured from the original model. Here the guides are at a slight angle while the set-out for the centre line shifts along the surface’s edge. In this way distances from the edges of the openings to the edges of the surface, while not being equal, are similar.

The parametric schema for the skylight openings was flexible enough to accommodate the changes – internally the openings retained their horizontal positions and the proportional system that had been elicited from the scanned model continued to adhere in parametric form. This test, while requiring some detailed investigation, served to illustrate that in the case of the skylight openings, the parametric model was satisfactorily flexible when accommodating construction information.

### 7.3 Observations for construction

The final section of this chapter extrapolates the output generated on the Docklands Tubes as a relationship between output in construction and output in manufacturing. When I introduced designing parametrically in Chapter Two, I noted the research overlaps with the domain of manufacturing industries from which the technology of parametrically controlled software is largely being transferred.

#### Docklands Tubes – factory made

The collaborative nature of the design of the process for the Docklands Tubes, between those not normally collectively associated with the design development of built work – artists, fabricators, students, programmers and surveyors in the case study – brought an unexpected method of representation to the project.

As with some of my other case studies, the design space in the Docklands Tubes adhered to constraints determined by fabrication methods. In this case study, output from the process was also designed to report fabrication information. This was a combination of the data describing the arc information that could be directly inputted to the CNC tube bending machine and the spatial locations of each tube with the relative twist angle between each part for assembly. The largest sculpture, entitled Shoal, contained 420 arcs in the entire sculpture conveying almost 3800 separated pieces of information. This collection of arcs was fully documented without
drawings, in tabular form in spreadsheets, with a digital model for cross referencing. Such methods of representation would be quite unfamiliar if placed amongst the conventions of representation of spatial data in most architectural practices.

**Figure 7.14** Curves fabricated from arcs, in the factory awaiting assembly.

The case study was further distinguished as being unusual in construction. It was fabricated from machine readable information and it was constructed off-site, inside a factory.

**Figure 7.15** Shoal, one of the Docklands Tubes sculptures, during construction.

In my research, the Docklands Tubes case study above all allowed me to follow a parametrically designed process to its conclusion. During fabrication, I received only one query that turned out to be a misplaced spreadsheet. When I wrote about the case study for a conference, I asked whether this project demonstrated the computer as an effective tool for designing and producing architecture. I suggested the Docklands Tubes served to illustrate the
point at which the computation can discernibly augment design, where an artefact is no longer well described through conventional methods.

My euphoria was tempered, however, as the sculptures for the Docklands Tubes did not directly move from factory to site. They were stored in a warehouse for a number of months as a dispute ensued. The dispute was not between any of the parties involved in the design of the sculptures; rather it was over who would install the works on site. The fabricators, as it turned out, did not hold the necessary workplace certificates to enter the construction site for which the Docklands Tubes were intended. Kieran and Timberlake (2004) identified site work practices and procurement methodologies as inhibitors for innovation in design and construction. Their research into innovative practices has also found similar issues emerging, specifically citing cases where fabrication occurs off-site.

Docklands Tubes prompted me to reflect on the context of the opportunity of practice-based research. Despite the existence of dedicated research and development departments in construction practice, innovation in project based work has been found to be extremely hard to capture. Little is transferred from one project to another or from projects back to the sponsoring organisations of the participants (Gann & Salter 2000). Additionally, systems and structures do not exist yet to transfer new knowledge gained from projects across the relevant disciplines or through associated industries (Taylor & Levitt 2004). Lawson et al. (2003) found that even when architectural firms work for clients who repeat commissions, lessons learned on projects are not channelled into similar projects, partly due to organisational contradictions between what the firm intends to do, and then what the members of the office aspire to, and then actually do, on future projects.

This means that formal structures and processes need to be established, or greatly enhanced, to ensure that research insights are transferred, debated and accumulated, for instance, to capture ‘tacit’ or inexplicit disciplinary knowledge.

As I considered the lessons from Docklands Tubes case study where the parties responsible for its resolution aligned in parallel to design a parametric process rather than applying their own processes of resolution and representation in sequence, I reflected that it is this uniqueness of process that differentiates the design of the built environment from product development. I studied accounts of the transformation of manufacturing industries through new tools and techniques, such as Womack, Jones & Roos’ tome on lessons learned in Japanese automotive industry – The Machine That Changed The World (1991). Karl Sabbagh’s account in film and book on the design and manufacture of Boeing’s 777 ‘21st Century Jet’ (1996) was also particularly influential as Boeing were also using CATIA, the software employed for the research on The Sagrada Familia. Boeing had to change work practices as well as modes of representation when moving from drawings to models.

In August 2004, the US National Institute of Standards and Technology (NIST) released its report into the Cost Analysis of Inadequate Interoperability in the US Capital Facilities Industry (Gallaher et al. 2004). The report draws on similar themes to my research,
namely inquiring as to why an industry has proved so resistant to transformation by digital technologies.

By quantifying a cost (estimated at US$15.8 billion) NIST offered a panacea for one of the major impediments the report identified to any change in practice – that a lack of incentive inhibits change. The Docklands Tubes – the only case study to be built using the research – served to provide a reminder that computing in architecture is but a component in the broader sphere of construction activity.

7.4 Conclusion

This chapter reflects upon the parametric model and the scale of the site, or of production, for the Docklands Tubes. In the case of The Sagrada Familia I found the parametric design was flexible when confronted with information gathered on site. In fact I extended the model to include a further skylight to test the flexibility, and when final surveyed dimensions arrived from the Technical Office, the parametric model for the Corbertes was satisfactorily varied to match the new positioning information.

I further tested the robustness of the design upon the delivery of the level and profile of an upper floor within the transept roof, and the parametric model was again adjusted to suit new positioning.

To test the question posed in the sponsoring ARC grant about the flexibility of parametric models, with external information I ran several experiments to capture inaccessible site measurements, extending tools found on site and some earlier research using photogrammetry.

I found, after some practice, that three-dimensional data from inaccessible areas was quite easily generated with relatively cheap software for digital photogrammetry. These techniques augment the tools of measurement used by the Technical Office.

Finally, I reflected on the production of the Docklands Tubes, the only case study to be built during my research, as a challenge both to conventional methods of representation and at a broader scale than the parametric model – its output has implications for the work practices in construction.
Endnotes

1 Martinell founded the Centre of Gaudinist Studies in 1956. In his book (Martinell, C 1975, *Gaudí: his life, his theories, his work*, MIT Press, Cambridge, Mass.) he refers to the position adopted by the association for the continuing construction of The Sagrada Familia. By popular vote, this was to continue the work by adapting Gaudi’s techniques and giving free rein to following architects. He states that strict adherence to the models should only apply to those Gaudí was relatively advanced with (pp.437-8) and rather tersely writes that at the time of publication the continuing construction was based on the drawings (the photograph of the original drawing for the Passion Façade).

2 The experimental nature of Clini and Fangi’s research is confirmed as it predates Heuvel’s estimate in his survey of the genesis of *CAD-based* photogrammetry by three years. (Heuvel, FAvd 2000, ‘Trends in CAD-based photogrammetric measurement’, *International Archives of Photogrammetry and Remote Sensing*, vol. 34, no. 5/2, pp. 227-32.)

3 Clini and Fangi observed that working in this way *‘the operator could be rather inexpert in photogrammetry but from the other side he should have a deeper knowledge in architecture’* (Clini, P & Fangi, G 1991. ‘Two examples of non-conventional photogrammetric techniques: the nativity’s interior façade and the spire of St. Barnabas’ bell tower in the Sagrada Familia – Barcelona’, Proceedings of Cipa XIV International Symposium, Delphi. p175)

Conventional photogrammetry is the use of photographs to make measurements especially in topographic mapping. Specially calibrated cameras and dedicated equipment are used to analyse the photographs. Newer methods of photogrammetry either non-conventional as Clini or Fangi described, or digital as I used, do away with the special cameras and equipment. These have been replaced by software can be used by non-technical people.

4 Domenec Sugranyes(1879-1938) is known to have collaborated with Gaudi from 1905 in the Sagrada as a second assistant after Francesc Berenguer, for whom he substituted as a first assistant 1914. After Gaudi’s death in 1926, he was charged with the direction of the construction works at the Temple He died in Barcelona in 1938 during the Civil War. (Noted from a poster in the Technical Office).
8.1 Discussion

Software in which geometric form is controlled through the definition of parameters and application of constraints has been recently adopted in architecture. It is known as parametric software and has its origins in mechanical engineering. Parametric software is widely used in the aerospace and manufacturing industries, and in architecture it offers as many challenges as opportunities in its use. In fact, one of the pioneers of computing in architecture, Charles Eastman, stated: ‘The expertise regarding rules for parametric boundary conditions is not widely available and will become a growing area of research’ (Sacks, Eastman & Lee 2004).

As I stated in Chapter Four, I used this quote to help formulate my research question; what are some of the boundary conditions when designing and working with parametric models in architecture? The aim of my research was to establish some of the boundary conditions and my hypothesis was that through the parametric modelling of complex forms, lessons for how architects can better understand the adoption of parametric design, more generally, could be revealed.

To test the hypothesis I used a methodology of practice-based case study research, in which parametric models were designed and tested, through several case studies of complex forms in the research. I was fortunate to have a sponsoring major case study through an Australian Research Council grant led by Professor Mark Burry. The ARC grant asked whether the flexibility of a parametrically designed model could accommodate the assumptions that must be made where accurate measurement is not possible. While I answered my research question, each of the case studies posed their own questions and, in turn, contributed to the overall research.

It made sense to me to structure the exegesis around the way the answer to my question was revealed through the work. This is done through three themes, each focussing on boundary conditions at various stages of a parametric model. The first, in Chapter Five describes the effort expended to structure a parametric design and I have used the chapter heading ‘Designing the design’ as the title of my research. I found designing the parametric design an essential activity as a precursor to a parametric model.

Once a model has been established a design space, or space of possible models is afforded and the boundary conditions for how architects might manoeuvre through such a space are addressed in Chapter Six entitled ‘Traversing parametric design’. I then concentrated on the resultant implications of parametric models in the broader construction sector in Chapter Seven.

I quoted Branko Kolarevic when introducing the notion of parametric modelling where he stated ‘the parameters of a particular design that are declared, not its shape’ (Kolarevic 2003). The statement points to the fundamental challenge for architects when designing parametrically which is the declaration of the design. Parametric modelling requires the
examination of process in architecture. Parametric models are computational constructs, and declaring one’s design moves form necessary steps. Explicitly revealing motivations for doing this or that will be challenging in a profession that has lost much of its domain of practice over the past half century to the rise in sub-specialisms.

However, I believe this requirement to design declaratively will provide opportunities for architects. The rigour of re-presenting a design so that it can be machine-readable will also serve to help to explaining design to other parties involved in the process. Having others understand the value of design will be crucial as my research documented, the extra effort required when gathering appropriate information for the implementation of a design strategy to develop a schema for parametric modelling.

I called this concentrated preparation for the schema, ‘designing the design’, and in doing so documented two predominant methods of schema creation I found in my case studies. These were, firstly, schemas based on eliciting rules relating to the methods of fabrication and, secondly, schemas based on realising geometrical design intent.

I found that the boundary conditions when designing the design relate to the tools, techniques and information at hand. Moreover, the boundary conditions may use sketches and verbal descriptions, but these require translation from tacit understanding to declarative description.

I experimented with methods for capturing existing model information including three-dimensional scanning. The application of scanning at The Sagrada Familia was the first time such techniques had been used on the project and allowed me to forensically assess the surfaces of Gaudí’s original models.

The investigation into the Corbertes skylights at The Sagrada Familia revealed the original plaster model contained the geometric schema for the design of the skylights. I found the design was based on a detailed proportional system some indication of the original methods used in its construction were given. I used the schema to design a parametric model that allowed the skylights of various sizes to be instantiated within the Corbertes.

Schemas based on methods of fabrication, such as The Docklands Tubes case study or the Parametric Bridge case study, expanded the number of parties contributing to a design. Fabricators, who often come to a project during its construction phase were required much earlier and their experience and advice were codified into the parametric model. The Docklands Tubes, for example, used information that could be machine-read by computer numerically controlled machinery that cut and bent sections of stainless steel tubes.

Front-loading the design process by placing extra effort at the early stages of a design will require greater remuneration for the work being carried out and clear explanation. It will also place pressure on methods of procurement when parties such as fabricators contribute and collaborate early in the design.

The limits of a parametric model are a boundary condition of its design. When a parametric design has been established, iterations of the resultant design space of a model can be tested
through varying parameter input. I examined the potential to traverse a parametric model as a
design space as well investigating opportunities to share the derived design space with other
disciplines.

In a lesson learned from The Sagrada Família, I theorised the parametric model as a digital
metaphor for the hanging model Gaudí’s developed for the form finding of the Colonia
Güell church. After a series of experiments, a collaborative design space that an engineer
and architect could simultaneously inhabit was made in the Parametric Bridge case study.
Conceptually, two disciplinary views were created into the one parametrically designed
space; the engineer’s view permitted the establishment of constraints to delimit the space for
acceptable structural conditions, and the architect’s view offered control of the geometrical
constraints. Once effected, the parametric model of the bridge responded to both disciplines’
desires and the space of resulting models could be explored interactively. An outcome of this
research is that I found designing parametrically can sponsor methods for truly collaborative
processes.

Later, with an optimisation algorithm enacted, the design space of the Parametric Bridge was
revealed to support two different activities. The parametric model could not only be explored
but also searched in a directed manner. Searching allows goals or targets to be set that an
algorithm can be designed to look for. Throughout these experiments, when the boundaries of
a design space were reached, I returned to the earlier assumptions made when designing the
design. I found the ability to edit a parametric model is required to revise early assumptions
when further information is known on a project.

The boundary conditions when designing parametrically were tested at the scale of a building
and the parametric models I designed from Gaudí’s original plaster remnants for the roof were
found to be robust and flexible enough to accommodate the information in the form of site
measurements that were delivered from The Sagrada Família church.

Finally, I reflected on the rules for the boundary conditions of parametric models in relation to
the broader systems of production and procurement in construction. This was done using the
Docklands Tubes case study, the only case study to be built during my research. I found the
output from parametrically designed processes can challenge not only conventional methods
of representation, but also at a broader scale, its output has implications for work practices
in construction. Using computer numerical control machinery, the Docklands Tubes were
formed off-site by technicians from outside the construction sector. The method of fabrication,
enabled through the parametric model, precipitated a labour dispute that prevented the
erection of the Docklands Tubes for months.

The work of capturing preconditions and processes, and then communicating issues that were
obscure or unknown outside of my contribution, is intended to establish a benchmark and
instruction manual for others.
8.2 Application of findings

In this section, I describe the application of the findings in my research for further work and I have organised them by title.

Finishes on the transept roof of The Sagrada Família

A module of the transept roof at The Sagrada Família church has been parameterised from the original Corberes model and the Technical Office of The Sagrada Família church has my research and reports. As the Corberes model is unadorned in detail, and without description of the intended finishes, I have taken the opportunity to speculatively show the transept roof form as it might be seen when finished.

The following images show the roof with finishes that may be applied. I have taken cues from photographs I took when I visited the Colònia Güell church, especially the tiling patterns around the reveals of the windows to the crypt.

On my final visit to The Sagrada Familia church I saw views of the research work pinned to the walls of the Technical Office overlaid with details for construction. I hope to have made some useful contribution to its ongoing construction and to Professor Burry’s larger work at the church.

Figure 8.01 Speculative detail of the transept roof with finishes at The Sagrada Familia church.
New forms of notation

Returning to the issue of the declaration of design, I believe there is an opportunity to develop a system of notation for parametric design. Words, drawings and images were used to convey design intention in an ad hoc manner in this research. The clearest record of the design left behind in the parametric models of the case studies are the comments made in the software code for the Space Division Case Study. They are related to the pseudocoded software that was used between architect and computer scientist and retain a conversation about the design intention. The parametric model within CATIA can be graphed and the relationships investigated but this requires effort and will be difficult for the uninitiated to make sense of the structure. Even returning to some of the models in which I was the sole author there is a difficulty in reading the design through the graphed relationships of geometry.

Parametric design is very much associated with each design’s author and this association is similar to the philosopher Nelson Goodman’s (1968) argument for the case when authorship and execution is united. Goodman introduced terminology to distinguish fine arts on the basis of notation. Where notation is discernable, such as musical notation, multiple instances of the work can exist independently of the author. So when Johann Sebastian Bach is heard today, the audience associates the work as Bach’s. As Goodman saw it, architecture although not built by the hands of architects, remained connected with its author as the means of transmitting the design, namely sketches in his view, exist without a system of notation.

I believe there is an opportunity to extend the research beyond the geometric databases in dedicated parametric software or commenting in software code to enable the recording of design intent through a notational system that offers a semantic representation of the parametric model and design intent.

Other systems of notation will offer guidance. Labanotation, a system of notation for dance,
might be useful. There have been several attempts at choreographic notation but Labanotation, dating from the 1920s, is the most widespread. It was developed to describe the movement of bodies in space using symbols to represent points on a dancer’s body, the direction of the dancer’s movement with the tempo and dynamics, and could be regarded as parametric in its vision of the body (Guest 2005).

**Machine readability and construction**

The research covered new forms of data acquisition as well as data output. The computer numerically controlled machines used for tube bending in the Docklands Tubes case study afforded representation that was machine readable, being the data in tabular form recorded in spreadsheets.

If the machine in the factory served to pull information from the parametric model for the Docklands Tubes, at the other end of the process, the three-dimensional scanners pushed digital data towards the model. In a small-scale, a digital supply chain was established from design to production.

In future, the demand for digital information in construction will be stimulated not by the enthusiasm of a few but by end-to-end systems that generate data with equipment such as sensors, and then demand machine readable information for construction.

Unlike manufacturing industries, demand for digital information in construction is currently low and further research in this area, both technical and economic, is required. My research and these case studies have captured my detailed observations of instances where digital information was productively deployed in architectural praxis on complex forms but this area can be generalised across the construction sector.

**The role of the researcher practitioner**

‘“Go into any architects’ office”, he claimed, “and 90% of what you see will be drawings”. “Yes”, I replied, “but 99% of what you hear will be words”. It is just that those conversations do not get recorded in the way the drawings do’ (Lawson 2005, p. 389).

Finally, I reflect on the design of the research, in particular project-based case study methodology where the researcher is also an active participant. Using the tools of the academy and trained in its methods, at times I was embedded within the context of practice. As I worked on the case studies, the notion of my role developed towards that of a researcher-practitioner. There is an opportunity to develop a new context within which to incubate new researchers, new research questions and methods. Arising from my research, there is evidence that applied research depends on research contexts, such as the character of the profession being studied, the kinds of research questions which arise from professional and industry sector concerns, and the challenges that technological innovations present in work places.
This type of research is socio-technical and further studies into social science and the relationship with new technologies in the workplace are required. Researchers within the context of professional architectural practice ought to be not only active participants in the design process, but also trained as observers. The broader research to which the ‘practitioner-observers’ can contribute could be implemented through a hybrid context of critical practice and social science.
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Appendix A  Published material during the research

Refereed papers


Book Sections

In addition Peter Szalapaj published the research from the Docklands Tubes case study in -

Appendix A

Introduction

This paper presents work in progress of an application of CAD-based digital photogrammetry for the purpose of providing further interpretation of historical images of drawings and models of the original work of the architect Antoni Gaudí (1852-1926). The projects discussed are the Passion and Glory Facades of the Sagrada Família Church in Barcelona. The work contributes to the broader effort of the research team to resolve the intended surfaces from a limited supply of information in order for construction to advance.

Digital photogrammetry, using software to make measurements from images, is now available in comparatively low cost commercial packages. The interdisciplinary combination of the fields of computer vision and photogrammetry has served to enlarge the scope of data acquisition and processing architects are able to deploy on a project. This is by making generally available the ability to generate three dimensional information through processing multiple two dimensional images. This can be accomplished without expensive recording equipment or analytical plotters. Concurrently, architectural description, is undergoing a profound

Hybridized Measurement:
Interpreting historical images of Sagrada Família Church in Barcelona using CAD-based digital photogrammetry.

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This paper gives an account of the extrapolated use of digital photogrammetry undertaken by the Spatial Information Architecture Laboratory (SIAL) in the pursuit for new interpretations of historical images at the Sagrada Família Church. The work is an extension of the research activities undertaken as part of the Australian Research Council (ARC) Strategic Partnerships with Industry – Research and Training (SPIRT) project New onto Old: 3D flexible computer modelling to aid heritage building restoration, recycling and extension, where digital photogrammetry was first explored as a measurement tool for non-specialist implementation. The research makes use of the link between Computer Aided Design (CAD) and digital photogrammetry in a reverse manner, using built spatial data to produce orthographic rectified images of what was intended from the historical drawings and models of the architect Antoni Gaudí (1852-1926).

Keywords: CAD-based digital photogrammetry, spatial information, measurement, interpretation.
transformation, one that other design disciplines producing physical objects have generally been through. It is a paradigm shift from the two dimensional plane into three dimensional space. This spatial data, its acquisition, manipulation, visualisation and extraction, present challenges and opportunities across the entire construction industry including architectural practice and education.

CAD-based digital photogrammetry refers to the integration of CAD and photogrammetry. A summary of its development and different approaches is discussed by van der Heuvel (2000).

The Spatial Information Architecture Laboratory at RMIT University (SIAL) has been investigating methods of three dimensional measurement and data collection, recording elements of the Sagrada Familia using digitizers, laser meters, three dimensional laser and optical scanners and digital photogrammetry. Extracting satisfactory facsimiles of Gaudí's combinations of ruled surfaces has challenged the scanning tools, most of which have their origins in the gaming and film industries. (Burry, Burry, Dunlop & Maher 2001).

Of the Sagrada Familia's three facades, the Nativity Façade was the only one to be constructed during Gaudí's lifetime. Its neo Gothic origins were inherited by Gaudí from his predecessor Francesc de Villar and are evident on the bare interior which stands awaiting further carving and statues upon its empty pedestals in striking contrast to the exterior that is covered with decorative finishes Gaudi daubed first with plaster and gradually replaced in stone. The Passion Façade, partially completed in the 1970's, represents the introduction of the geometry developed by Gaudí to construction. The Glory Façade, which is to be the main entrance is yet to begin. Surveys of the existing built work at the Sagrada Familia are essential, mainly due to the destruction of the drawings during the Spanish Civil war.

The genesis for this research began during a site visit when amid the ongoing construction activity, direct access for measurement was not available to the interior of the Nativity Façade, being partially obscured by levels of scaffolding and construction platforms. To date detailed photogrammetric surveys for the Passion Façade and the Apse have been carried out by the Topography department of the Universitat Politècnica de Catalunya (UPC). With further survey work not imminently scheduled, CAD-based digital photogrammetry is being explored as a technique for gathering three-dimensional data through the use and adaptation of laser measurement and digital photography, both employed by the technical office at the Sagrada Familia (figure 02). It is envisaged the results of the research will both serve to extend the use of such tools and skills on site, and the retrieved spatial data will be used to acquire three dimensional digital models in the form of proxies of the existing building fabric, to then establish the relationships and associations in parametric software between the old and the new. Such methods lie beyond the site measurement skills of most architects but may be highly valuable when contrasted as an intermediary with the more complete and accurate surveys of the UPC.
The development of CAD-based digital photogrammetry as an interpretive tool discussed in this paper differs from our research on the Nativity Façade and other similar approaches such as Bae et al. (2002). It was undertaken with the partial absence of measurable built structure. The Passion Façade, is a ‘mixed media projection’ of the image of Gaudí’s drawing of the Passion Façade using survey data, while the Glory Façade is attempted through various means including reconciling original images with a present-day plaster model.

The Passion Façade and the original 1917 drawing

The Passion façade as it is today (figure 03) was constructed between 1954 and 1977. Current work has been for the near complete rose window (Burry, Burry and Fauli, 2001), and investigations for the colonnade, consisting of a column and gable assembly above the cornice, of which only a single photograph of a drawing for the façade exists. This drawing is by Gaudí, dated 1917 (figure 04) and indicates the use of forms derived from the combination of ruled surfaces which were in the process of development during the last twelve years before his death in 1926. It is the primary source for the entire façade.

During the 1970’s a 1:25 plaster model of one side of the colonnade was interpreted and completed under the direction of one of Gaudí’s former collaborators Puig i Boada and completed by Cardoner and assistants during the 1980s (figure 05). This model has been topologically digitized by the SIAL and the columns are currently undergoing a process of generative development (Burry, Burry, Dunlop, Maher 2001). The half model introduces a
degree of ambiguity to the question of the symmetry of the entire composition.

The original photo, approximately eighty years old, clearly shows an architectural elevation almost perpendicular to the projection plane. It is assumed to be taken with a bellows camera, although little information about its purpose or exact date are known. Of particular interest is to understand the relationship of the camera to the photo of the drawing. If survey data from the 3D model could be used to orient the drawing further interpretation could be made of its apparent asymmetry. Was it intentional or a result of the camera angle? Did the drawing take into account the fall of the site and what is the difference between the drawing and what has been built?

Interpretation

The aim of the project was to create an orthographic image of the original Gaudí drawing – an architectural elevation. Where it is impossible to
regain information, assumptions have been made and their declarations serve to weigh the importance of the work in relation to current body of knowledge and state of construction. The hybrid nature of the rectification locates three dimensional coordinates from the actual building and then projects through the drawing to the object itself. The cornice in the drawing is treated as though it were a photo of the actual built work. Figure 06 shows a comparison of an orthographic image of the existing Passion Façade by the UPC, with Gaudí's original drawing.

PhotoModeler Pro by EOS Systems Inc. was used for this research. A single photo project was established and control points, three-dimensional points of known location, were imported from the existing features in the UPC survey (figure. 07). Corresponding points along the edges of the cornice, the doorway and the cornice columns were identified.

The absence of the fiducial properties of the original camera used were solved by processing the project as an inverse camera operation. Such an operation establishes parameters for the unknown camera using the imported control points as constraints. In this situation the camera is located as though it were photographing the actual building. It is unknown whether the drawing was on an angled wall or within a frame. To eliminate distinguishing between perspective within the object itself and the perspective within any ‘out of plane’ relationships of the drawing it was assumed the drawing was hanging planar. The position of the camera was identified as rolling 1.35 degrees about its direction vector and being 2.80 degrees from centre vertically and 0.83 degrees from centre horizontally.

Planar control points were identified and used to create and export an orthographically rectified image (Figure 10) or elevation.

**The orthographic image and its possible interpretations**

This research indicates that through this unorthodox use of photogrammetry another interpretation is possible. The resultant image opens several avenues of interpretation of the colonnade. Most notably is the effect of symmetry and alignment. The drawing which appears at first to be more suggestive of a symmetrical relationship of columns is now indicating a more pronounced ‘stagger’. With Gaudí's interest in forms derived from nature and the human body, the similarity could be described as to a rib cage. The difference in height evident in the columns will inform the development of the SIAL's parametric modelling design for the columns.
The Glory Façade and the original model

The Glory Façade, celebrating the resurrection, is the main entrance to the church. It is also the least documented of the facades with only two photographs of an original model by Gaudí in existence (Figures 11 & 12). The model shows an arrangement of sixteen spires of hyperboloids of revolution surrounding four bell towers, whose proportions have been identified with those throughout the church. The project follows that of the Passion Façade and the primary investigation was to compare the photos in isolation and generate an orthographic image of the original model. However the absence of possible processing constraints (photos, axes or control points) inherent in such geometrical forms pose significant hurdles to retrieving spatial data. In isolation there is little prospect of extracting any information from the images alone, due to the lack of camera information and the resultant perspective of the forms.

The physical location of the original model can be discerned by the architectural elements in the photograph. These were re-established as control
points through the creation of a simulated model of the scene, but failed to produce a result. In the future actual identification of the space may allow information to be gathered on the possible location of the camera and the model and their relationship to one another.

Another hybridized method of referencing external data is now in development. There is a present-day plaster reconstruction of part of the Glory Façade model that has been made by the Sagrada Familia workshop (Figure 13). Measurements have been clearly taken from the photographs as the markings are still visible. Using CAD-based digital photogrammetry a three-dimensional digital model was generated by the SIAL of the plaster model to check the validity of deriving the surfaces in such a manner. Combined with a prior geometrical the digital model was found to be dimensionally accurate by comparison.

Several iterations of the project were carried out initially with only the two photographs. To enhance the level of constraint, later iterations of the project included the addition of the locality data and finally three dimensional control points from the present day model. PhotoModeler would in fact only process once camera information was given, and the results of the Passion Façade were used. This is not a true representation of the unknown camera though, as the camera used was most likely a camera which would not have repeatable settings.

The project as reported is still a work in progress. A new variation to the methodology, in order to build a more comprehensive database of the model and its environment is proposed. Scanning and digitizing tools will be used to capture highly accurate and detailed information of the present day plaster model generating control data to orient the original photos. Initial research has indicated the possibility of processing a successful project. Such a method would introduce a second abstraction, using a present day model – itself an interpretation to generate a further interpretation of the original. Such a method though, would embody the transmitted knowledge of Gaudi’s collaborators with the skills of the technicians in Sagrada Familia workshop; approaching a digital craft through the combination of the original intention with the experience of the hands that make the objects.

Conclusions
The research shows an interpretive approach through the development of the link between low cost commercial digital photogrammetry software and CAD. It may broaden the use and the way architects deal with computers and design, in this case by furthering engagement with the object for the purpose of a hybridized measurement.
Acknowledgements

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DESIGN MODELS FOR CROSS DISCIPLINARY COLLABORATION

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SUMMARY

This paper describes work carried out at the Spatial Information Architecture Laboratory at RMIT University. We discuss new research opportunities available through the use of high level design software that facilitates cross-disciplinary collaboration using 3-dimensional digital models in shared environments. Using current research examples, we illustrate how such software may now offer real time access to structural analysis simultaneously with architectural design. The paper attempts to convey how the principles by which architects and engineers might now engage digitally may be well founded in history by, using the architect Antoni Gaudi’s (1852-1926) famous funicular hanging models as a metaphor of the kind of digital space that is imagined.

INTRODUCTION

The architect/engineer Felix Candela (1910-1997) said in 1954, 'In the field of construction we fortunately are ending a long, analytic period. The ideas that nourished it are fully developed and to continue exploiting them would be senseless. If the symptoms are to be believed, we are on the verge of a new creative epoch. Architects should be pleased with this situation, especially if they manage to regain their position as 'master builders', since in order to build at such a time it perhaps will not be necessary to master so much science but to have some talent’. (Stereo structures, June 1954 Progressive Architecture.)

Candela was referring to the analytic methods of algebra and calculus that during the 20th century had all but subsumed other more intuitive but less scientific, graphical techniques in engineering. The claim was made at a time when he was finishing the Inglesia de la Virgin Milagrosa church in Mexico, acknowledging the structural calculations that confirmed the design were actually made some time after the documentation was finished. However his assumption that such a period was ending, was premature. It has been argued that while engineering as praxis did possess a unique position between technology and science, many innovative techniques and works were ignored and lost in its evolutionary process of analysis (Billington 1983).

The aim of this paper is to lay the basis and provide a historical context for the work in progress at the Spatial Information Architecture Laboratory (SIAL) at RMIT University into the opportunities for cross disciplinary collaborative design environments between architects and engineers offered by high level computing and the associated developments in computer graphics visualisation.

The research led by Professor Burry, a Gaudi scholar, into parametric design computing has its foundation in the ongoing construction of The Sagrada Familia Church in Barcelona. Here, such advanced 3-dimensional techniques fit hand-in-glove with forms designed a century ago that have resisted conventional architectural description.

The pedagogical imperative is to be found in the architectural design studios at RMIT University, where students at first struggle with the requirement to design a 'schema' that can be then be parametricised to create variable forms.

Such design software has been developed for the aerospace and manufacturing industries and is out of the reach of most architectural practices. It is also antithetical in approach to conventional
architectural software (Wittenoom 1999). Concurrently Finite Element Analysis (FEA), the computationally intensive method of analysing the mechanical properties of materials or structures is migrating to the desktop computers of engineers. However it is still little used by structural engineers who generally work through the rationalisation of building forms to a set of planes for which sets of analytical equations can be applied. Dr. McLachlan's research uses finite element methods shape optimisation of design parameters to vary the structural forms of bells and arrive at required tuning.

We believe the integration of these approaches, both architectural and engineering offer the flexibility to optimize forms through declared parameters providing a unique working environment while simultaneously reinforcing each as a design discipline.

THE FUNICULAR MODELS OF ANTONI GAUDI

The dominant view of the architect Antoni Gaudi (1852-1926) is of the isolated genius, with much of the inspiration for his work generally attributed to attaining a synthesis with nature. Such a view however, overlooks some interesting and potentially illuminating developments in science, mathematics and architectural education of his time.

Gaudi used his famous 3-dimensional funicular hanging models to arrive at his unique solutions. He first employed them on the Colonia Guell church (1898, 1908 - 1914), where the scaled model was hung in a workshop creating a dialogue between his assistants who would upon instruction, shift the bags of lead about to vary the form, which would then be photographed, turned upside down and rendered to give effect to the form. This unique process was done with both the interior and exterior of the church. (Figures 1 and 2.)

Gaudi spent 10 years on the design before the first stone was laid in 1908. Although only the crypt for the Colonia Guell church was completed, the derivation of form and the synthesis of structure and model are unmistakably evident. Not only did this funicular model provide a method of communication between Gaudi and his assistants, but with his engineer, Mariano Rubio y Bellve, it also provides a forum for cross disciplinary collaboration.

The 3-dimensional model was a form of the graphic methods of analysis, an engineering practice common at the turn of the 20th century, and familiar to Gaudi and his contemporaries, most famously
the engineer Eduardo Torroja (1899-1961) and Felix Candela. Graphic methods of analysis allowed the exploration of forms not easily analysed before its introduction. Of great influence to Gaudi was the work of the French theorist Eugène Emmanuel Viollet-le-duc. It is known Gaudi returned a book he borrowed by the architect much thumbed and notated. Viollet-le-duc, was influential at the time for his restorative work and although Gaudi would have not sympathised with his love of Gothic structure, or his atheism, he was clearly influenced by structural rationalism.

However it is interesting to speculate that Gaudí’s criticism of Gothic buttresses as crutches might have been influenced by the work of the French Beaux Arts professor Julian Guadet (1834-1908). Guadet’s combination of the French gothic and classicist traditions, (known to have caused disagreement with Viollet-le-duc) led him to produce an alternative proposition for the gothic church of St. Ouen show the flying buttresses of the original church replaced with a parabolic structure (Figure 3.). Guadet arrived at this scheme through the application of graphical methods of analysis and it is certainly possible Gaudi, who exhibited in Paris in 1910 could have made contact with it. The proposal was published in Guadet’s *Elements et theorie de l’architecture*, which was still widely assigned as a text book past the mid 20th century.

![Figure 3. Guadet’s critique of the Gothic church of St Ouen. A parabolic proposal using graphical methods (left) and the original (right).](image)

**THE DEVELOPMENT OF GRAPHICAL METHODS OF ANALYSIS**
The lineage of graphical methods for structural analysis and representation has its roots in the 17th century. Galileo, amongst others, attempted to synthesise structural forces by combining mathematics and material behaviour. However, it was the Swiss engineer, Karl Culmann (1822-1881) who developed the representation and analysis of the body of work of statics; the branch of mechanics concerned with forces in equilibrium, by using graphical methods based upon projective geometry that became known as graphic statics. Culmann published his work, *Die Graphische Statik* in 1866.

Graphic static methods are somewhat antithetical to analytical mathematical methods, and are often described by comparison with the application of technology to the development of science. It is through Culmann that graphic methods are strongly identified as a Swiss engineering tradition. David Billington in *The Tower and the Bridge* suggests there is also a cultural answer, lying somewhere between French structural empiricism and Germanic scientific theory.

Graphic analysis promotes an intuitive approach to the design of structures. In fact many of the bridge designs by the Swiss engineer Robert Maillart (1872-1940) could not be analysed analytically at the time and were largely the result of observation judgment, model making and experience. Maillart’s remarkable bridges developed with his adaptation of the graphic techniques, from the Tavanasa Bridge, a three-hinged arch of 1905 to the decidedly more structurally complicated Schwandbach Bridge, integrating a vertical arch with a curved road. (Figures 4 and 5).

Billington relates that by mid century, the analytic mathematical methods rendered much of Maillart’s work indecipherable using engineering scientific theory that resulted in the works being ignored for many years.

**Figure 4. Tavanasa Bridge 1905**  
**Figure 5. Schwandbach Bridge 1933**

Culmann’s successors at the Swiss Institute of Technology (ETH) in Zürich continued the development of the graphical methods, encouraging artistic endeavour to flourish by further shedding extraneous analysis. Of the schools graduates, the shell structure designer, Heinz Isler (1926) who began his career mid century also used inverted modelling techniques, while the architect/engineer Santiago Calatrava is a current exponent of the techniques.

**Models and modelling – Parallel developments in science and technology**

Graphical solutions and their analytic counterparts are broadly represented in the development of the fields of science and technology. In mathematics, the graphical methods of Gaspard Monge’s (1746-1818) descriptive geometry (and later Poncelet’s projective geometry) were supplanted by analytic methods using algebra and calculus. This largely grew out of the work of Rene Descartes (1596-1650) and the representation of space as points or Cartesian co-ordinates – the space we create 3-dimensional digital models in. In contrast with engineering, design as a science never really expanded deeply into architecture, and the lineage of architectural representation firmly rests today with Monge’s graphical origins.

By the early 20th century in most technological endeavours the scientific principles and methods dominated. Mathematicians had, between the 18th and 19th century’s used plaster and wood models to aid the visualisation of geometrical concepts, in a similar way to the use scale models for observational and analysis in engineering schools. The writer Manuel deLanda in his essay ‘Uniformity and Variability’ extends this view to the mechanization of the 19th century, correlating the loss of craft skills in favour of the exactitude of a scientific understanding of the world, with the decline
of empirical knowledge of the complex nature of materials. deLanda calls for ‘the need to nurture again our ability to deal with variation as a creative force’.

Computing and Finite Element Methods

It is only with the advent of computer graphics that mathematicians have started to graphically represent analytic equations. In engineering too, computing and the visualisation rendered through powerful graphics processors allow the most numerically intensive materials analysis – using Finite Element (FE) methods.

Finite element analysis uses the power of computing to analyse digital models. In Finite Element Analysis (FEA) complex geometries are divided into small elements defined by geometric nodes that can be described mechanically by analytical equations. The equations are linked together in large matrices by the computer in order to describe the behaviour of the complete form. Used for many years in the aerospace industry, through the ubiquitous supply of powerful computing it has migrated to engineering desktops. It is not commonly used in building design, as building structures tend to be broken down into 2-dimensional planes where elements or sub-assemblies can have the rules of statics applied. However, with more complex building forms FE methods become a critical tool for locating the stress concentrations. The results of such numerically intensive processing are only as good as the input, although with knowledge in its application FE analysis does posit the proposition of an iterative method of digital design engineering

PROJECT ONE: FE MODELLING AND SHAPE OPTIMIZATION OF BELLS

Bells and other idiophones are unique amongst musical instruments in that they naturally produce inharmonic overtones. This is because, unlike air-columns and strings that vibrate predominantly in one dimension only, bells vibrate flexurally in three dimensions. Flexural vibrations are much more difficult to describe analytically than longitudinal vibrations and it is common to use numerical methods such as FEA to predict the behaviour of bells and gongs (McLachlan 1997, McLachlan, Hasell and Keramati Nigjeh 2002, Perrin and Chanley 1983). Pre-developed, commercial Finite Element (FE) software was employed to implement a classic linear finite element method for the work on the bells (Tomas 2000).
Given the ability to solve complex problems using numerical methods, shape optimisation can be applied to bell models to adapt wall profiles and where possible, arrive at specific tuning ratios of partial frequencies. Design optimisation applied to FE models usually involves creating the model with a number of shape parameters that can be varied during the optimisation process to achieve a certain objective such as tuning to a target set of natural frequencies. Geometrical constraints such as maximum allowable mass, and behavioural constraints such as specific natural frequencies, often need to be applied to the design process to obtain useful solutions. For bells, the shape parameters used to define the bell profile could include angles, lengths, and offsets of lines, or the relative positions of points used to create spline curves. Optimisation could then involve a systematic evaluation of the design space (defined by the design constraints) through the generation of a set of models representing all possible combinations of shape parameters at certain levels of discretisation. The optimum design solution can then be found by polynomial curve fitting to the values of the objective across all design variables. This is likely to be the most time consuming approach! Other optimisation methods can be used to reduce the number of analyses undertaken to achieve a satisfactory solution. These include curve fitting to data generated by making random jumps through the design space, or gradient projection methods.

Gradient projection methods compute the changes in the objective as a function of changes to a range of shape parameters in an iterative process. After each step the gradient of the objective function is used to predict the direction the next step should take. A gradient projection method (Fox 1971) was utilized for the bells in order to optimise the objective function by changing the coordinates of the FE nodes themselves, rather than global shape parameters. The user may select a zone of active nodes with coordinates that will vary during optimisation. The design sensitivity of the objective is calculated from differences in the objective parameter after displacement of each active finite element node. The process of optimisation then iterates towards a target in accordance with geometric constraints that preserve shape parameters of the model such as symmetry about the vertical axis.
the optimisation process. The optimisation process stops if progress toward the optimisation target cannot be achieved without altering the constrained parameters beyond a given tolerance.

The user sets the step size used in the first iteration of the optimisation process. It is also possible to define a reduction rate for the step size in the following iterations in order to prevent the optimisation from overshooting the target and then alternating on either side of it. The initial step size and its reduction rate were carefully selected based on experience with similar models.

PARAMETERS AND PARAMETRIC DESIGN

Using FE analysis to optimise geometry in a collaborative environment between disciplines such as architects and engineers is now possible with software such as CATIA from Dassault Systemes. CATIA offers a series of discipline specific ‘workbenches’ that operate on a single digital model. Workbenches include finite element analysis and geometric modelling with solids and surfacing. Appropriate packages can be applied by their relevant disciplines and we envisage the possibility of analysis directly optimising geometric forms through declared design parameters.

With cross-disciplinary collaboration, such design parameters would serve as the digital dialogue between the disciplines. This would serve as an extension beyond the understanding of each disciplines boundary and in this manner we may see the beginning of a digital version of Gaudi’s funicular model.

Such a level of collaboration, especially between architects and engineers requires a number of fundamental shifts, not least in representation to the understanding of 3-dimensional models controlled with design parameters.

PROJECT TWO: THE DIGITAL MOCKUPS DESIGN STUDIO

In the first semester of 2002 a design studio was jointly run between with the School of Architecture at the Massachusetts Institute of Technology (MIT) and the SIAL at RMIT University with the architectural practice of Gehry Partners, LLP. The studio was structured as a collaborative venture exploring the potential for both remote collaboration and the application of advanced computer modelling techniques of parametric design and associative geometry within a design and design development context.

The studio was based upon the development of a ‘reading room’ developed through parametric design approaches. The work was developed simultaneously at all three locations, and through a shared online working environment accessible to all project participants. Collaboration took place through “parametric re-use”, where teams swapped earlier designs and continued to develop the parametrically defined designs, with the encoded “solution spaces” of these designs could be explored or refined by project members. The studio spanned the entire architectural design production process, from initial representation, the development of ‘variable models’ through to the fabrication of physical and virtual prototypes and assemblies.

Here students began the process of articulating an architectural project with a series of design parameters. Figures 6 and 7 show some examples of the analysis of material properties and surface curvature, through the use of the different workbench tools available in CATIA software.
CONCLUSION

The potential for a cross-disciplinary design interaction exists within collaborative software environments, particularly. We have introduced some projects which take this on and placed them in a within a historical context which suggests much of value could be achieved through such exercises. We hope to report on one of these in the near future. FEA with shape optimisation is a form of parametric design in which a relatively simple form of artificial intelligence is applied to sets of design parameters that are too great for humans to systematically resolve. It provides a platform by which both engineering and design solutions may be achieved simultaneously, enabling a fluid transition of design ideas with engineered outcomes.

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The Parametric Bridge: Connecting Digital Design Techniques in Architecture and Engineering

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Abstract

New design opportunities that are facilitated by cross-disciplinary collaboration in both practice and research are available through the use of high level design software that simultaneously offers real time access to both analysis and design geometry in shared three-dimensional digital models. Here we present a collaborative research project between architects and structural engineers for the design of a pedestrian bridge, conceived to test current digital design processes in architectural and structural engineering practice with those in research through the use of models of parametrically defined associative geometry.

In this project, the digital model’s architectural design geometry was constrained by the bridge’s fabrication methods and linked with its engineering analysis. Iterations of the design geometry were then optimised or ‘solved’ to produce variations according to the design parameters offered up for change.

The shift of the professions from the plane to digital space exposes the possibilities of new design techniques with the exchange of design parameters potentially operating as a digital dialogue between the disciplines—a kind of digital version of Antoni Gaudi’s funicular hanging model—a metaphor of the digital space that has been developed for this project.
1 Introduction

This paper describes work undertaken for a parametric solution to an Arup bridge design. Concurrent with the design and construction of an actual bridge, the research was conceived as an attempt to test current design processes in architectural and engineering practice with those in research through the use of models of parametrically defined associative geometry. This approach sponsored a collaborative study across the disciplines of structural engineering and architecture through a system using a single digital model that shared geometrical constraints linked to its fabrication method, and material and loading analyses which could then be iteratively regenerated or optimised towards targeted solutions. The use of a single model significantly differentiates the research from other investigations into architect/engineer collaboration such as Klercker (2002). Cross-disciplinary and collaboration are both widely used terms with an inferred interdependence, and both have positive as well as negative connotations. With ever increasing specialisation in design, much is to be gained from developing ways of broadening the traditional barriers of disciplines (Garz 2000). In distinguishing our research as collaborative we recognise that in fact it is more likely to be co-operation, the premise of the relationship between professionals, occurring across disciplines far more often and equally deserving in research (Kvan 2000). It is interesting to note though, that much research in cross-disciplinary thinking presupposes that the disciplines to be bridged are those already within a professional coterie. While this is in no way to be discouraged, there is much potential in drawing from outside sources. Our project used high-end software intended for the manufacturing and aerospace industries which necessitated a renewed approach to the design from both disciplines. This process of technological transfer facilitated a system of parallel and mutually dependant actions which were cross-disciplinary yet not essentially of either discipline.

In broadening the framework of the interaction entailed in this research project it has been helpful to review terms which approximate the activity in research from other fields. In interaction design “joint activity,” a close-coupled interaction which is procedurally based might be useful in describing the “collaborative” result of our visual optimisation. While “mixed initiative,” a responsive dialogue between human and machine, might better describe our “cross-disciplinary” system, expanded in this project to interact discipline to discipline via machine. In that context the declarative process used to inform the parametric model is the common language local to the project, and the exchange of design parameters, the digital dialogue between the disciplines—a digital version of Antoni Gaudi’s funicular hanging model, a metaphor for the digital space that has been developed in this project.

The research was undertaken in both Melbourne and London. The parametric model was developed in Melbourne, remotely from the project team and the periods of intensive collaboration were undertaken “on site” in London. This was partly due to the infancy of design spaces for online collaboration and partly due to its secondary role as a forerunner for an “embedded” research strategy where well equipped mobile post graduate students will spend part of their project based research collocated in practice, the other reflecting outside it.

1.1 Project description

The project is for the pedestrian bridge at the new Selfridges store in Birmingham UK. Future Systems are the architects. The bridge links the store with an adjoining carpark, over a busy road, which circumnscibes the larger inner urban development known as the Bullring, in which the store is located (Figure 01). The curved and seamless bridge is a difficult form to realise. Arup London Group Four was supplied with a digital model by the architects, and a fabrication method was sought through the tendering process. A revised model was then built which conformed to the selected fabricator’s requirements. It was transformed into an analysable mesh by Arup’s Advanced Technology Group and analysed in Arup’s structural analysis package, a procedure taking one person working exclusively, three months to complete. While it could be expected subsequent iterations would not take as long, a considerable investment in time would still be required, and at a significant cost.

The aim of the research was to investigate the above process with a parametric model, so that in close to real time, iterations of the bridge could be generated thereby realising the design space—of structural engineering and architecture through a system using a single digital model that shared geometrical constraints linked to its fabrication method, and material and loading analyses which could then be iteratively regenerated or optimised towards targeted solutions. The use of a single model significantly differentiates the research from other investigations into architect/engineer collaboration such as Klercker (2002). Cross-disciplinary and collaboration are both widely used terms with an inferred interdependence, and both have positive as well as negative connotations. With ever increasing specialisation in design, much is to be gained from developing ways of broadening the traditional barriers of disciplines (Garz 2000). In distinguishing our research as collaborative we recognise that in fact it is more likely to be co-operation, the premise of the relationship between professionals, occurring across disciplines far more often and equally deserving in research (Kvan 2000). It is interesting to note though, that much research in cross-disciplinary thinking presupposes that the disciplines to be bridged are those already within a professional coterie. While this is in no way to be discouraged, there is much potential in drawing from outside sources. Our project used high-end software intended for the manufacturing and aerospace industries which necessitated a renewed approach to the design from both disciplines. This process of technological transfer facilitated a system of parallel and mutually dependant actions which were cross-disciplinary yet not essentially of either discipline.

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the use of the computer to augment the description of form is well founded where that form resists conventional architectural description.

Three dimensional digital models in architecture are not yet well established beyond visualisation tools. Digital modelling, simultaneously and interactively, as an immersive editing process in practice is virtually unknown. Parametric design however, through the association of geometry, allows form to be controlled through the definition of parameters and application of constraints, which when manipulated can generate families of forms (Burry 1999). In proposing strategies for design structure in digital environments such high end software, developed for the aerospace and manufacturing industries, offers as many challenges as well as opportunities in its adoption to architectural design. In cost alone it is out of the reach of most architectural practices and being athetical in approach to explicit "one off" modelling (Wittenoom 1999). It requires at the outset the development of an initial declarative schema, which then drives the design.

Research into applying parametric techniques to architecture has been led by Burry through the ongoing construction of The Sagrada Familia Church in Barcelona (Burry 1993). Here the process is informed through the research into the codex of ruled surfaces Gaudi developed during his final twelve years. Similarly the complex digital modelling undertaken by the architectural office of Gehry Partners LLP (Calf. US) is determined through the primacy of the physical modelling methods used in the office. Glymph et al. (2002) show how Gehry Partners has used parametric design to describe freeform glass structures.

In our research a number of suites of parametric modelling software are utilised, and parametric techniques are often applied through programming. This project uses CATIA by Dassault Systemes, software developed originally for aerospace, but now used widely in the automotive industry. Parametric modelling in CATIA has been introduced in its current incarnation, version 5. In addition, CATIA offers a range of analysis methods and a set of tools for manipulating the information known as Knowledgeware, all exploited in this project.

2.1 Building the parametric model

The purpose of the parametric model for the bridge was to constrain its geometry to the fabrication methods selected for its construction. The bridge’s underside or tray is steel, and the canopy is polycarbonate supported by steel hoops at varying angles from the deck which rises and falls gently to suit disabled access. The successful tender for the bridge was based on bending steel tubes (side tubes at the deck’s edge and a main tube on the underside,) in two directions to achieve the three dimensional curves that form the bridge’s tray. The tubes were then to be cut down along their bi-tangent intersection and the sides infilled with steel plate. This method was preferred to another proposal which would have approximated the tray’s surface to facets (Figures 02 and 03).

The hierarchical database of the parametric model was constructed by first interrogating the explicit model, supplied by Arup from Rhino NURBS modelling software, to gain an understanding of the geometry. Three guiding curves were extracted from the edges of the tubes in the original model and resided at the top of this database, so the parametrically variable tray could be varied to suit different tube sizes while maintaining the bi-tangency of the sides within the boundaries of its perimeter. The polycarbonate canopy followed suit, depending on the successful regeneration of the tray but also operating within its own fabrication constraints.

At any point along the tray an intersection made with the surface by a plane normal to the curve will be found to be circular in profile and of the same dimension as the ends, confirming the topology of a tube.

Bi-tangent lines between these tubes form the underlying structure of tray’s sides. A ruled surface was placed between the tubes (Figure 04), which was then developed with little deformation. The benefit of describing a surface in this manner is that, materially dependant, the surface can be then cut out of a flat sheet and rolled or offered up to position. (Fully developable surfaces are those which can be unrolled onto a plane without deformation, a cylinder being one of the easiest to visualise.) The steel hoops share the same principle but at each instantiation are unique. In this case a parametric feature was designed to regenerate itself for the varying conditions each time it was repeated. The hoops vary at increasing angles along the bridge length and are made from steel flats laser cut and fabricated into T-sections (Figure 05). However, the T-sections are not perpendicular, as the flange is always parallel to the polycarbonate (providing an even surface for fixing) while the web is in the plane of the rotating axis.
The guide for the hoops was the polycarbonate top which was defined in a manner not dissimilar to the tray, although without any explicit geometry. The centre line of the deck was found about which a 2700mm radius tube was extruded. The bi-tangency was then found between the outside tubes of the tray and the tube to establish the surface. Intersections with this top guiding surface were made with the ability to move up and down the bridge and vary in angle.

2.2 Variations and comparison
The constraints were tested and variations made to compare the parametric tray with the original Arup model. With the guiding curves constraining the model’s design space, the main tube could be varied between 500mm in diameter up to 1750mm in diameter. Variations were then rapid prototyped in wax and comparatively measured; proportions of tube to plate and dimensional variation from the original (Figure 06). In fact, during the project supply was the most important issue, with the final tube switching from 1050mm diameter to 900mm due to unavailability of the larger size.

The parametric model was developed in Melbourne, with a physical model reviewed in London. Communication during this period was mainly asynchronous, textual via email and often supported with explanatory images. Models, drawings and sketches of details were exchanged, but the overall volume of such material was minimal. In fact the process of distilling written information was found to be invaluable in founding the declarative process which in turn was used to define the parametric schema.

3 Analysis
Speculation about the ability to leverage the finite element analysis and advanced meshing tools in CATIA for use in structural engineering led to an investigation of the single model concept, opening discipline-specific views to the parametric model. Finite element methods are computationally intensive and have only recently migrated to the desktop of engineers. In finite element analysis complex geometries are divided into small elements defined by geometric nodes that can be described mechanically by analytical equations. The equations are linked together in large matrices by the computer in order to describe the behaviour of the complete form. Used for many years in the aerospace industry, they are not commonly applied in structural engineering, as building structures tend to be broken down into two-dimensional planes where elements or sub assemblies can have the rules of statics applied. However, with more complex building forms finite element methods become a critical tool for locating critical stress concentrations.

3.1 Analysing the parametric bridge
In establishing a structural engineering view of the bridge’s parametric model, our collaborative process began by passing a portable computer between engineer and architect, constructing a single digital space while sketching and writing ideas to convey each other’s principles, toggling views of the model between analyses and geometry, and vice versa.

Arup’s in-house structural analysis software is called GSA (General Structural Analysis), incidently an almost identical acronym to CATIA’s (Generative Structural Analysis). For this purpose the paper refers to ‘Arup GSA’ and ‘CATIA GSA’ so as to distinguish between the two. Comparative results using finite element meshing and analysis require different methods to conventional structural engineering analysis. A one-dimensional beam (stick meshing), two-dimensional surface mesh, and three-dimensional volumetric mesh were used to first corroborate the results between both Arup GSA and CATIA GSA.
For the purposes of the research, the tray and deck of the bridge were determined to be an acceptable approximation of the form for the structural analysis. The bridge’s cable restraints were later added. A two-dimensional surface mesh was generated on the parametric model and a finite element analysis performed to determine the bridge’s displacement and stress. Through the discipline specific view of the structural engineer, this operation involved the addition to the project of local axes and restraints at the ends of the bridge, linear loads, and the application of material qualities including thickness (Figure 07). A routine of meshing the parametric model and computing the result of the analysis in CATIA GSA then followed any modification of the bridge’s design geometry.

3.2 Variations of the parametric bridge

Through the Product Engineering Optimiser, a Knowledgeware function in CATIA, parameters can be optimised to a target value, be it minimum, maximum, or given. Free parameters are then offered for variation and steps and ranges can be set. Two algorithms are used by CATIA, a localised Gradient “hill climbing” method or Simulated Annealing, which adds in some randomness to offer the potential to “jump” the hills and further explore a design.

Consideration was given at this point to the flexibility of the design space. The parametric model had been limited by the design curves, which were explicit and therefore without parametric variability. As already shown, iterating through the free parameters in the geometric model which were related to tube sizes had already mapped the potential variation. In seeking to extend the perimeters of the form and increase the parameters which affected it, the parametric model was rebuilt so the guiding curve for the main tube, the underside of the bridge, was defined by a combined curve (the result of the intersection of the extrusion of two curves). This process was also informed through reviewing the strategy with the architects. A vertical parameter controlled the depth of the bridge and when added with a horizontal parameter, the combined curve freed up the position of the model in space. This operation required carefully re-editing the parametric database to replace the explicit curve with a parametric curve. This was time consuming and is at the limits of redefining hierarchical parametric geometry.

Several scenarios were then designed for optimisation (Figures 08 to 10). Every iteration during optimisation requires the consistency of the model’s database. In the bridge’s case, this means adhering to its fabrication constraints. Each model outputted could therefore be identified as a tube deformed in two directions with bi-tangential sides of ruled surfaces. The values of each parameter used in the optimisation routine are recorded at each change in a spreadsheet (Table 1. provides an example), and the configuration at each iteration interpreted at a later stage. By simply resetting the parameter’s values states can be selectively revisited if so desired.

The displacement analysis results generated from CATIA GSA were used as targets for the following constraint solving optimisation procedures using the engineering analysis to visually optimise the form. The process then, to understand the scope of what might influence a model’s geometry and its potential design space, becomes increasingly important in a collaborative sense to all those taking part in the mediation of the artefact.

4. Collaboration

Today, the potential of finite element methods recalls an earlier enthusiasm for the graphic methods of statics, an engineering
Appendix A

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practice developed late in the 19th century. Structural analysis through graphic statics allowed the exploration of forms not easily analysed before its introduction. The funicular hanging models Antoni Gaudi used to arrive at his unique solutions were in fact three-dimensional graphic analyses. He first employed them on the Colonia Guell church (1898, 1908 - 1914), where a scaled model was hung in a workshop creating a dialogue between his assistants who would, upon instruction, shift the bags of lead about to vary the shape, which would then be photographed, turned upside down, and rendered to give effect to the form. This unique process was done with both the interior and exterior of the church (Figures 11 and 12). Not only did this funicular model provide a method of communication between Gaudi and his assistants, but as a structural analysis tool it also provided a forum for cross-disciplinary collaboration.

Proximity and face to face contact, it would seem, are still essential to seed collaborative processes. Two key meetings were held for this project when the authors were in London, one at its inception and one for review. These were followed by periods of research and reflection in Melbourne. Then a final intensive session of collaborative work on the single model was undertaken while collocated at Arup in London. In our research project, we found that synchronous technologies, which generally mimic conventional communication, such as web chatting, internet meetings, and video links at best augment the design process. These essentially serve to perpetuate connectedness, and in doing so reinforce the absence of communication tools that support the heterogeneity of complex processes that inform the act designing.

Collaborating on a single digital model between two separate disciplines demands more than document workflow facilitation. A bi-directional flow of information not normally associated with communication between the disciplines is required. Our team extended beyond architects and engineers; in this project mathematicians and fabricators were also authoritative. A design structure which can be influenced by structural analysis and optimised to target a visual solution adopts and borrows techniques from both disciplines, and yet cannot be expected to be of either discipline. This certainly has implications for the adoption of traditional methods of communication when collaborating.

4.1 Extending the process

The research drawn from this project could be extended in two directions. Firstly, to what extent can the process be adopted to delimit the boundaries of a design space at the conceptual stage? Although the case for parametric design is well founded at a detailed design stage, how might this collaborative process be applied when dealing with the incomplete knowledge inherent at the beginning of a design project? Conceptual analysis tools such as the Evolutionary Structural Optimisation method (Xie 1997) might be useful in establishing a cross-disciplinary dialogue.

Secondly, automation techniques in fabrication could be investigated when linked to parametric databases. How might the intersections of bi-tangency be inscribed onto a tube or could the hoops be constrained to minimize wastage based on efficient cutting patterns?

5 Conclusion

Through the sponsorship of the parametric bridge project we have been able to examine the potential of a digital design model offering cross-disciplinary collaboration between architects and engineers. While parametric modelling might at first be regarded as another specialisation, here we have shown an approach or technique for possibly understanding equally well architecture and structural engineering.

This work involved considerable technology transfer, adopting methods from outside the fields of architecture and engineering, and challenging established techniques in each discipline. As the outcome of the research could be considered greater than the input of each contributor, it could be said to be a truly collaborative process.
Table 1: Example of changing parametric values during optimisation.

<table>
<thead>
<tr>
<th>Iteration</th>
<th>Maximum Displacement (mm)</th>
<th>Cable Restraint Location (mm)</th>
<th>Tube Vertical Location (mm)</th>
<th>Tube Horizontal Location (mm)</th>
</tr>
</thead>
<tbody>
<tr>
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<td>12798</td>
<td>1484.59</td>
<td>5745.23</td>
<td></td>
</tr>
<tr>
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<td>14385.8</td>
<td>1466.18</td>
<td>5739.07</td>
<td></td>
</tr>
<tr>
<td>23.4008</td>
<td>13228.7</td>
<td>1538.32</td>
<td>5767.56</td>
<td></td>
</tr>
<tr>
<td>23.4008</td>
<td>12449.3</td>
<td>1441.57</td>
<td>5775.39</td>
<td></td>
</tr>
<tr>
<td>23.4008</td>
<td>11784.1</td>
<td>1507.41</td>
<td>5824.81</td>
<td></td>
</tr>
<tr>
<td>23.4008</td>
<td>12797.7</td>
<td>1484.57</td>
<td>5745.18</td>
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<td>12567.7</td>
<td>1439.34</td>
<td>5741.03</td>
<td></td>
</tr>
</tbody>
</table>

Scenarios with three or four free parameters were run for approximately seven hours at a time—not yet a real-time process, but indicative of the processing power required. The location of the bridge’s restraining cable was iterated along the length of the deck, and the curve of the main tube was freed horizontally and vertically.
Figure 11. Gaudi’s hanging model.

Figure 12. Inverted photographs used to render forms.
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Research Team

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Future Systems are the architects for the new Selfridges store in Birmingham.
Building Blobs: Embedding Research in Practice

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Abstract. Through a model of engaging research in practice, we present the development of a technique for digitally resolving three-dimensional curves for documentation and fabrication. We suggest it is possible to distinguish the power of the computer as a design tool in the design development process, where the description of complex forms are not well served by the established methods of orthogonal representation.

Keywords. Architectural representation; complex form fabrication; practice-based research.

Introduction

Responding to the conference theme we might ask why is the computer considered to be an effective tool for creating and producing architecture? Is it perhaps to the extent the conventions of traditional architectural representation have been adapted to the digital realm? In this paper we suggest that one point at which the computer can discernibly augment design can be illustrated where an artefact is no longer well described through conventional methods.

Describing complex forms

Complex three-dimensional forms are challenging to document and construct using orthogonal representation. The architectural historian Robin Evans (1995) cited the example of the difficulty in realizing Hans Scharoun’s Berlin Philharmonie as it was translated from sketches and models to working drawings.

Physical modelling techniques have been used to advance the design development and construction of challenging buildings such as the Sydney Opera House and The Sagrada Familia Church in Barcelona. In the case of The Sagrada Familia Church, the use of modelling concurs with Gaudi’s codex of intersecting ruled surfaces, a system partly developed to aid complex form description (Burry 1993). Vollarers (2001) has recently used ruled surfaces as a method of fabricating non-orthogonal architecture through the development of ‘twisted’ window framing systems.

Digital modelling by contrast is generally not well established in practice beyond a visualisation tool. In education however, the profusion of relatively inexpensive software using mathematically defined curves such as non-uniform rational b-splines (NURBS), has afforded rapid form creation and experimentation. In this manner, designing using the computer has offered students a fluidity often leading to, at the more geometrically difficult end of the spectrum, curvaceous shapes or ‘blobs’.

Although rendered visually seductive, such forms can be critically challenging as they emerge from their transferral to an architecturally readable artefact (Burry 1999). Techniques often require ‘slice and dice’ operations to extract two-dimensional profiles for the overlaying of conventional drawing techniques in order to produce plans, sections and elevations. Further development can...
become reduced to a sectional stitching process imposing a rigidity described in practice as necessary for construction in ‘contractor space’. This is also where forms claiming to be animate have been criticised for being ‘frozen’ at their point of architectural documentation.

In this paper we reflect on design research for the development of a technique for documenting and constructing three-dimensional freeform curves. The work was undertaken by researchers and students at RMIT University’s Spatial Information Architecture Laboratory (SIAL) in the context of our practice-based research programme. Despite the existence of dedicated research and development departments in construction practice, innovation in project based work has been found to be extremely hard to capture (Gann and Salter 2000). Our research programme responds to this with a dual role methodology of design research for both practice and education. Its intention is to offer technical resolution at one point while sponsoring other types of design activity – a particularly important function of the student involvement.

Three-dimensional curves proliferate in digital space, yet curves in built space are generally planar, separated into tangential arcs during the shop drawing process and fabricated by welding similar profiles of different lengths and radii. Although assemblies of planar curves have been used to give three-dimensional effect (Figure 1), the ability to build three-dimensional curves has the potential to ascribe a consistency between NURBS models in digital space and real space.

A method for doing this is to use circular profiles. By twisting tangential arcs relative to one another it is possible closely to emulate the construction of fully three-dimensional curves? Automotive exhausts made from several bends and straight tubes welded together in this manner are probably the most complex curves now constructed. An analogy in architecture would be the fabrication of well designed continuous hand rails. Using the computer to develop this project’s design rendered drawings superfluous to the task of transcribing over 10,000 individuated pieces information. We see this type of enquiry as a possible stimulator for design computing across all stages of the architectural process.

The Shoal Fly By project

Shoal Fly By is a public artwork comprising a collection of five separate sculptures intended to represent movement through water (Figure 2). Two artists, Cat Macleod and Michael Bellomo, hand crafted models at a scale of 1:100 composed entirely of freeform curves using wire as their malleable medium. In this way they could capture small bends and kinks, a ‘seamless yet not smooth’ aesthetic they wanted to retain in the final work to be built in stainless steel tube. The sculpture had been awarded first prize in a competition for construction on the foreshore of the
docklands precinct in Melbourne, which is currently undergoing massive redevelopment and as a place to work and live.

The Shoal Fly By project is the second of four projects in the current practice-based research programme, exemplifying the process of embedding our research within practice. Students were sponsored both to take part in the activity and to return the results in a manner promoting reflection on their own academic design work. Our research in this case was to develop a design development process that transferred scaled freeform curves into digital space, transcribing the curves as tangential arcs for a computer numerical controlled (CNC) tube bending operation followed by fabrication through their full size spatial relocation.

The artists had previously built relatively simple curved forms in steel, developing an appreciation of the fabrication processes involved. Through their own research they knew that without establishing tangential relations between the constituent parts of the work the result would be an exposition of joints, preventing a reading of the whole - in this case the network of freeform steel tubes.

The modern process of tube bending has its foundation in the 14th century when developments in methods for bending brass resulted in a musical horn of conjoined tubes - the forerunner to the trumpet. Today the bending of tube can be accomplished through highly controlled CNC processes where the tube passes either through rollers or around a fixed die. Most bends are planar and of fixed radius, although it is possible to offset the radius to draw a helical extrusion.

The students started by attempting to accurately and effectively measure the physical model. Beginning with a point probe on a three-dimensional digitising arm, repeatability of the wires on the scale model proved inaccurate. This led to a non-contact method using a laser scanner with sub-millimetre clouds of points. The wires were then traced from points to NURBS curves.

An algorithm was developed to approximate the wires to a series of tangential arcs. This involved assimilating the information required by the tube bending machine and for the fabrication procedure with a method for separating the NURBS curves to arcs. This is mathematically difficult and the result is always an approximation. This is because a curve is continuously changing in curvature whereas an arc is of fixed curvature and so steps through curvature changes. Our algorithm developed as we made visual iterations, finishing with eight constraints which could be varied for each curve such as minimum arc length, radius and maximum curvature change.

Interestingly an amount of tacit knowledge was developed in applying the procedure when reconciling the physical design with its expression in arcs. The artists didn’t want a “smoothed” result so a balance was sought between using a greater number of smaller arcs for a very close approximation and longer arcs with fewer joints to

Figure 3. Non contact measurement. Laser scanning a scale model

Figure 4. Approximating a curve as tangential arcs. Three variations.
Appendix A

achieve a more economical budget (Figure 4).

The collaborative nature of the work, between those not normally collectively associated with the design development of built work – artists, fabricators, students, programmers and surveyors in this example, brought an unexpected method of representation to the project.

Output from the process was continually adjusted to report fabrication information. This was a combination of the arc data that could be directly inputted to the CNC tube bending machine and the spatial locations of each tube with the relative twist angle between each part. The largest sculpture contained 420 arcs conveying almost 3800 pieces of information, which was fully documented using spreadsheets with a digital model for cross referencing. Although such methods of representation are common in our research, they would be quite unfamiliar if placed amongst the conventions of most architectural practices.

Returning the research

Alongside this project, the students used the methods to reflect upon their own work. Figure 5 shows the results of one student who reinvestigated her design studio project using the isoparametric curves of the NURBS surfaces of an apparently amorphous form, to guide a structural system. The process of applying three-dimensional design development to a digital model instigated a reappraisal of the design, perhaps offering a view to a use of the computer as a design tool.

Figure 5. Another application. A student using isoparms to guide a structural system (in black)

Conclusion

In concluding and returning to the conference theme, we suggest that one reason for the apparent under exploitation of the power of the computer as a design tool and as a design stimulator may be due to the paucity of established methods to represent complex forms created using the computer. Through the results of our practitioner-based research, we have developed a technique to encourage more detailed and rigorous design development of digital models. This potentially offers an opportunity for the use of the computer for design and is surely of benefit to students, educators and practice alike.

Acknowledgements

The Shoal Fly sculpture is by the artists Cat Macleod and Michael Bellemo. The authors wish to acknowledge and thank the SIAL Summer Scholars, Lee-Anne Khor & Rebecca Naughtin.

References

Calvo, C. 1993, Some Epistemological Concerns Regarding Artificial Intelligence and Knowledge-Based Approaches to Architectural Design - A Renewed Agenda, Education and Practice: The Critical Interface ACADIA Conference Proceedings, Texas USA.
The Parametric Bridge Selfridges
Birmingham, UK

Axelrod Maher

Appendix A
Appendix B  Exhibitions and presentations of the research


**Corberte wax model from a work-in-progress stage, early 2004**

This model is designed to print at a scale of 1:50 giving an overall height as an assembly of 144mm. The length can be continued indefinitely by further printing corberte segments (01-03) and their mirror symmetries in equal numbers.

**Figure B.01** Guide developed to instruct Cambridge Galleries with model assembly
The research for the alternative version of the facade of the Beijing Olympic Pool was exhibited at the Architecture Biennale in Beijing in 2006.

Figure B.02 The poster exhibited at the Architecture Biennale in Beijing in 2006
**Conference Presentations**

Spatial Interface conference, University of Westminster  
April 2006

ACADIA conference, Ball State University  
October 2003

eCAADe conference, Graz Univeristy  
September 2003

ANZASCA conference, Deakin University *(Presentation Prize)*  
November 2002

eCAADe conference, Warsaw University  
September 2002

**Invited lectures, workshops and exhibitions**

2nd Beijing Biennial ( Emerging Talent, Emerging Technologies)  
October 2006

Transcapes Symposium, UTS Sydney  
November 2006

The New Geometry, RAIA presentation at Tusculum Sydney  
October 2006

Invited Presentation, MIT  
May 2005

Workshop on Digital Strategies for Architecture, Auckland University  
October 2004

Australasian Catia Forum at the National Manufacturing Week, Melbourne  
May 2003

Victoria University, Wellington  
April 2003

Australian Decorative and Fine Arts Society, Adelaide  
May 2002

**Selected invited practice presentations**

Arup, New York  
October 2006

Skidmore Owings and Merrill, New York  
October 2006

Alsop Partnership, London  
September 2003

Arup, Sydney  
June 2003

Hopkins Partnership, London  
March 2003

Arup, London  
September 2002, March 2003
Appendix C  ARC SPIRT grant details

3101 ARCHITECTURE AND URBAN ENVIRONMENT

ARC Grant Number:  C00107322
Prof Mark Cameron Burry  Deakin University  CI
Mr Sambit Datta  Deakin University  CI

Industry Partner(s):
Sagrada Familia Church, Barcelona, Spain

Australian Postgraduate Award(s) Industry (APAI) awarded :  1

Administering Institution:  Deakin University

New onto Old : 3D flexible computer modelling to aid heritage building restoration, recycling and extension.

Summary:
When working with existing buildings assumptions need to be made when accurate measurement is impossible, and where construction information is hidden within the existing building fabric. In these situations architects might benefit from interactive (rather than static) computer-aided design models. Three-dimensional models are becoming routine in practice, but their innate precision is in opposition to the 'loose knowledge' implicit with recycled building stock. The aim of this research is to apply and evaluate flexible modelling techniques (parametric design) developed by the research team to a case study of international importance: the continuing construction of the Sagrada Familia Church in Barcelona.
Appendix D  Case study project credits and supplementary images

Only a fraction of the images from the research and designs are used in this document. These images are supplementary to the short descriptions of the case studies in Chapter Four. They are provided for further interest and are not annotated.

Case Study One: The Corbertes at The Sagrada Família
Undertaken with an Australian Research Council Grant
Partner: Technical Office at the Sagrada Familia church in Barcelona
Chief Investigators: Prof. Mark Burry and Prof. Sambit Datta
Case Study Two: The Jersey Waterfront Bridge Competition

Industry Partner Michael Hopkins and Partners: Michael Taylor

Professor Mark Burry and Andrew Maher of the Spatial Information Architecture Laboratory (SIAL) at RMIT are part of the winning team for a new footbridge to provide access to the development of the St Helier waterfront area on the Island of Jersey.

Consulting with the architects Michael Hopkins and Partners, SIAL assisted with the definition and realisation of the complex 3-dimensional geometry of the arched bridge.

The work builds upon PHD research (ARC Spirit) conducted by Andrew Maher at SIAL, into the potential for cross-disciplinary design collaboration between architects and engineers using high level parametric design techniques.

From the Press release... www.jerseywaterfront.je

Jersey’s Waterfront Enterprise Board has announced the winning entry in the competition to design a footbridge to help Islanders get to and from the new developments safely. The winning team is the Flint and Neill Partnership, which was the first choice of the public, the technical advisory panel to the board and the board members themselves.

“I’m delighted we all came to the same conclusion and put the Flint and Neill design in first place”, says Geoff Borman, WEB’s finance director. "Islanders who voted for Flint and Neill described it as simple, an elegant landmark for the Island, a view which was shared by WEB members and the expert technical panel. I would like to thank everyone who took the time to let us know which was their favourite design”.

FaulknerBrowns took second place in the competition, with Hartigans and Studio Bednarski completing the prize winners in equal third place.

The majority of Islanders supported Flint and Neill’s design. Top local artist Ian Rolls described it as “a beautiful sculpture which could be stunningly lit at night”, and other voting slips called it “simple and modern”, and “elegant, a real gateway and a landmark structure”.

The expert technical panel which assessed all six shortlisted designs in the competition described Flint and Neill’s plan as an “exciting” design which:

“...generates a strong image by incorporating a suspended footbridge from, the curved arched structures, and is integrated into the promenade and approach from the town”.

The final result of the competition from an initial entry of 47 was as follows:

1) Flint and Neill
2) Faulkner Browns
3) Studio Bednarski + Hartigans
4) Wilkinson Eyre
5) Babtie
6) Ribble

Michael Taylor from “Michael Hopkins and Partners” was the architect on this design.

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Case Study Three: The Parametric Bridge (I & II)

Industry Partner Arup: Jan-Peter Koppitz and Ed Clark, Alvise Simondetti and Dr Kristina Shea (R&D)

(The design of the bridge was by Future Systems)
Case Study Four: Docklands Tubes

Industry Partner: Michael Bellemo and Cat Macleod
Tube Bending: BENDTECH Industries
Fabrication: Olivetti Engineering
Computer scientist: Peter Wood
Students: Lee-Anne Khor and Rebecca Naughtin
Case Study Six: Space Division, the regular irregular facade

Industry Partner Arup: Peter Bowtell and Tristram Carfrae
Yamin Tengono: Computer Scientist
Case Study Five: Digital stereotomy

Industry Partner Arup: Peter Bowtell and Toby Clark
Yamin Tengono: Computer Scientist

(The design for the Australian War Memorial in London is by architects Tonkin Zulaikha Greer and artist Janet Laurence and they were not involved in the research.)
Case Study Seven: The Suspended Arc

Industry Partner: Sandra Selig
Final Presentation Material

The material used to present the research for examination consisted of a large format poster and a touch screen interactive display.