2014

Parametric Tools in the Design Process

Robert B. Marcalow

University of Massachusetts Amherst

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PARAMETRIC TOOLS IN THE DESIGN PROCESS

A Thesis Presented

by

ROBERT B. MARCALOW

Submitted to the Graduate School of the

University of Massachusetts Amherst in partial fulfillment

of the requirement for the degree of

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Department of Art, Architecture, and Art History
PARAMETRIC TOOLS IN THE DESIGN PROCESS

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DEDICATION

To Cristina, my reason for living.
You are a source of constant support, and I couldn’t have done this without you.
ACKNOWLEDGEMENTS

First and foremost I would like to thank my advisors Kathleen Lugosch and Caryn Brause, who have been a constant source of support, and have engaged me in rigorous, meaningful discourse about this thesis. This research has grown in breadth and depth as a result. Caryn, thank you for all your help with just about everything, and for getting me involved with digital fabrication on campus; I would be on a very different path otherwise. Keep the Bunny running!

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ABSTRACT

Parametric Tools in the Design Process

MAY 2014

ROBERT B. MARCALOW, B.A., PITZER COLLEGE

M.ARC., UNIVERSITY OF MASSACHUSETTS AMHERST

Directed by: Professor Kathleen Lugosch

The recent revolution in digital design tools is having a sea-change effect on the way buildings are designed. As the design process becomes increasingly automated, the focus of architectural expertise is shifting from the execution of drawings to the parametric definition of space and form. In other words, the architect will define a complex set of rules that, when entered into a program, create a building. This design process, coupled with digital fabrication, allows for control of the final product in ways that were previously impossible for designers. However, there is still much to learn about the ways these new tools can be integrated into the architectural design and construction process, and their effect on that process. This thesis proposes that there are five levels of parametric design, varying in level of integration and complexity. The three most complex and visionary levels of integration were tested in three full-scale design-build projects to explore the ramifications of a computational process on design. A freestanding lamp, a chair for a teacher and a barn for two donkeys were designed using parametric tools at three levels of integration. Throughout each project, particular attention was paid to the steps in the design process, the effect of parametric integration on designer agency, and the role of labor in design and construction.
TABLE OF CONTENTS

Page

ACKNOWLEDGEMENTS .............................................................................................................. v

ABSTRACT ..................................................................................................................................... vi

LIST OF TABLES ........................................................................................................................... vii

LIST OF FIGURES ......................................................................................................................... xi

CHAPTER

1. INTRODUCTION ..................................................................................................................... 1

2. HISTORY OF PARAMETRIC DESIGN .................................................................................... 5

   Origins ......................................................................................................................................... 5

   Systems ...................................................................................................................................... 8

   Form .......................................................................................................................................... 13

   Contemporary Considerations ................................................................................................. 15

   Contemporary Criticism ........................................................................................................... 20

3. PARAMETRICISM .................................................................................................................... 24

4. PRECEDENT STUDIES ............................................................................................................ 29

   Endesa Pavilion ....................................................................................................................... 30

   Serpentine Gallery Pavilion ..................................................................................................... 35

   Boston Harbor Islands Pavilion ............................................................................................... 38

5. PROJECT FRAMEWORK ......................................................................................................... 43

   Levels of Integration ............................................................................................................... 44

   Validation ................................................................................................................................. 45
Building Information Management (BIM) ......................................................... 46
Parametric Elements ......................................................................................... 47
Fully Parametric Description ........................................................................ 48
Generative Formfinding ................................................................................... 50
Initiating a Parametric Approach .................................................................... 51

6.  LIGHT SKIPPER LAMP ............................................................................ 54
Concept .............................................................................................................. 54
Measurement and Evaluation .......................................................................... 58
Selecting a Winner ............................................................................................ 61
Fabrication ....................................................................................................... 62

7.  CHAIR FOR CRISTINA ............................................................................ 67
Concept .............................................................................................................. 67
Material Strategy ............................................................................................... 70
Fabrication ....................................................................................................... 72

8.  BARN FOR TWO DONKEYS .................................................................... 74
Site Review and Precedents ............................................................................. 74
Parametric Element 01: Siting Evaluations .................................................. 75
Conceptual Development ................................................................................ 79
Parametric Element 02: Ruled Roof Surfaces ................................................. 85
Parametric Element 03: Vented Siding ............................................................ 97
Final Design ..................................................................................................... 102

9.  FOCUS 01 – PARAMETRIC PROCESS .................................................. 111
Parametric Process in Design of the Light Skipper Lamp.................................111
Parametric Process in the Design of the Chair for Cristina .........................113
Parametric Process in the Design of the Barn for Two Donkeys .................114
Summary of Parametric Steps ........................................................................117

10. FOCUS 02: AGENCY IN DESIGN ................................................................119
    Agency in the Lamp Project .....................................................................120
    Agency in the Chair Project ....................................................................120
    Designer Agency in the Barn Project ....................................................121

11. FOCUS 03 – LABOR AND PARAMETRIC DESIGN ......................................123
    Labor and Parametrics ..........................................................................123
    Lamp .....................................................................................................127
    Chair ....................................................................................................128
    Barn .....................................................................................................129

12. CONCLUSION .........................................................................................130
    Final Remarks .......................................................................................132
    BIBLIOGRAPHY ....................................................................................133
# LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Ergonomic characteristics and requirements for the chair.</td>
<td>69</td>
</tr>
<tr>
<td>2. Barn program requirements.</td>
<td>80</td>
</tr>
<tr>
<td>3. Rafter tails and seats marking and cut process by step.</td>
<td>96</td>
</tr>
<tr>
<td>4. List of siding cut lengths.</td>
<td>100</td>
</tr>
<tr>
<td>5. Process steps in design and manufacture of the lampshade.</td>
<td>112</td>
</tr>
<tr>
<td>6. Process steps in design and manufacture of the chair.</td>
<td>114</td>
</tr>
<tr>
<td>7. Process steps in design and construction of the barn.</td>
<td>116</td>
</tr>
</tbody>
</table>
# LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Geometric diagrams that define the visual requirements of a soccer stadium in mathematical parameters.</td>
<td>6</td>
</tr>
<tr>
<td>2. Field diagrams describing “visual appetite” derived from the geometric principles established in Figure 1.</td>
<td>7</td>
</tr>
<tr>
<td>3. The resulting Stadium form.</td>
<td>7</td>
</tr>
<tr>
<td>4. Christopher Alexander’s Julian St. Inn, a homeless shelter in San Jose, California.</td>
<td>10</td>
</tr>
<tr>
<td>5. A diagrammatic representation of Christopher Alexander’s design workflow as laid out in <em>A Pattern Language</em>.</td>
<td>12</td>
</tr>
<tr>
<td>6. Frank Gehry's Guggenheim Bilbao was one of the first buildings to use mathematical algorithms to shape individual panelized elements.</td>
<td>15</td>
</tr>
<tr>
<td>7. <em>Atlas of Novel Tectonics</em> in relation to other movements.</td>
<td>16</td>
</tr>
<tr>
<td>8. An approach to thinking about materials.</td>
<td>17</td>
</tr>
<tr>
<td>9. Reiser + Umemoto’s diagrammed approach to form-finding</td>
<td>19</td>
</tr>
<tr>
<td>10. The final result, a canopy at the Rodelph Shalom synagogue in New York.</td>
<td>20</td>
</tr>
<tr>
<td>11. The heuristics of <em>Parametricism</em>, from Patrick Schumacher’s 2008 lecture, “Parametricism as Style: Parametricist Manifesto.”</td>
<td>25</td>
</tr>
<tr>
<td>12. Le Corbusier’s Villa Savoie contrasts simple geometry, accentuating their difference.</td>
<td>26</td>
</tr>
<tr>
<td>13. Zaha Hadid’s Heydar Aliyev Cultural Center in Baku, Azerbaijan uses non-primary geometry.</td>
<td>26</td>
</tr>
<tr>
<td>14. The Endesa Pavilion in Barcelona, Spain.</td>
<td>31</td>
</tr>
<tr>
<td>15. The Pavilion’s “solar bricks,” with solar panels above.</td>
<td>32</td>
</tr>
<tr>
<td>16. Calculating solar bricks based on sun angles for the Pavilion using Ecotect.</td>
<td>33</td>
</tr>
<tr>
<td>17. The Interior of the pavilion. The solar bricks are hollow, and create storage and seating spaces.</td>
<td>33</td>
</tr>
</tbody>
</table>

19. The pavilion’s structural system. Short members intersect each other at midspan (Architectural Design No 6, 2005).................................................................................................................................36

20. A site plan of the pavilion, showing the deflection around the trees (Architectural Design No 6, 2005)..................................................................................................................................................37

21. Utile's Boston Harbor Islands Pavilion in Boston, Massachusetts. ......................39

22. The mold for the Pavilion's spout was fabricated offsite, then cast in situ. ...........41

23. A diagram showing the relative complexity and integration of the five levels of parametric integration proposed in this thesis. ...............................................................45

24. Ahlquist and Fleischmann's 2008 exploration into generative formfinding in architecture resulted in a building envelope. .................................................................51

25. mA-style Architects' Light Walls House explores the concept of oblique light falling on a textured surface........................................................................................................54

26. Categorical selections led to a formal strategy. ......................................................56

27. Diagram of the controls over the lamp form.........................................................57

28. This formula creates a dissipating ripple centered on a point. .............................58

29. Octopus is a multi-dimensional evolutionary solver that compares many individuals against multiple criteria.........................................................59

30. Pareto frontiers in multiple dimensions ...............................................................60

31. After Octopus solves for the optimal individuals, the designer is faced with a field of 'equals' .......................................................................................................................62

32. The sections of the lamp mold being cut by a CNC router. ....................................64

33. The mold was used to form pasted calligraphy paper, then removed..................64

34. Routing the base from poplar................................................................................65

35. The final lamp design............................................................................................66

36. The chair was designed for a range of use configurations to encourage movement.69

37. The parametric controls over the chair enabled precise design. .........................71
38. The chair was cut using a CNC router. .................................................................72
39. Chair assembly was performed by hand. .............................................................73
40. The finished and assembled chair. .......................................................................73
41. Various run configurations used different sets of constraints and criteria. ........78
42. Overlaying the various runs reveals a concentration of optimal sites.................78
43. Diagram placing programmed elements on a spectrum between spaces primarily for donkeys, and those for humans. .................................................................81
44. Concept diagram placing the barn in the cycle of hay growth and digestion. ........82
45. Various linear gradient massing options were explored. .......................................83
46. A metaball model of the building with point charges by programmed area and activity level. ........................................................................................................84
47. The Escuela Sagrada Familia by Atonio Gaudi uses a ruled surface for its roof. ....86
48. Santiago Calatrava’s Bodegas Ysios in Laguardia, Spain uses large Glulam beams to create a ruled roof form. .................................................................86
49. Surfaces cannot be folded and maintain four straight edges without a crease. ....88
50. The projected shape of a surface changes when it is folded....................................89
51. The Frank Residence addition by Happy Box Architecture explores the ruled surface roof. ........................................................................................................91
52. Early formal explorations of the barn form............................................................92
53. The massing process diagram shows transformations to the mass to produce particular effects in the building.................................................................93
54. The two spheres with radii equal to the edge lengths define a path for the adjacent corner. ........................................................................................................94
55. The top plate cut tool scribes the correct angles without measurements............95
56. The rafter tail cut tool marks the end cuts. ............................................................96
57. Sequence of marks and cuts of a typical rafter. .......................................................97
58. Initial gradient siding options generated in Grasshopper. .....................................98
59. A concept model showing the siding transition strategy. ........................................99
60. Nailing diagram for blocks and boards in siding system........................................101
61. Diagram showing siding marking and cut process..................................................102
62. The view of the barn from the approach along the road. .......................................103
63. Site map showing approach, donkey paddock and barn..........................................104
64. The barn's east elevation is the first visible upon approach. ....................................105
65. The south elevation provides light and openings to the donkeys..............................106
66. The rainwater collection system provides warm-season water to the donkeys on demand.........................................................................................................................106
67. The west elevation provides access to the donkey quarters......................................107
68. The first floor plan of the barn. .................................................................................108
69. The second floor plan of the barn. ..............................................................................109
70. The view of the vented siding from the hayloft. .......................................................110
71. Isamu Noguchi's Akari Light Sculptures used simple molding fabrication techniques. .................................................................................................................................128
CHAPTER 1: INTRODUCTION

The last ten or so years have witnessed a revolution in architectural design tools. Parametric design – a term only recently considered obscure and largely academic – has become an integral part of many practices, thanks in large part to the advent of simpler and more user-friendly tools such as the Grasshopper plug-in for Rhinoceros and the built-in parametric tools in BIM-capable modeling programs like Revit and ArchiCAD. The effect on architecture is tangible: design magazines such as Architectural Record and Architectural Design are full of new projects – built and conceptual – that utilize parametric design in some fashion. However, the ecstasy of invention occurring at this moment is more of an exploration of new tools rather than the application of those tools to architectural concepts. This exploration is incredibly important and, better yet, thrilling. The excitement and energy surrounding the exploration of parametric tools (as well as the digital fabrication techniques that bring these digital concepts to fruition) is most evident on internet forums, where, in opposition to standard systems of property management and copyrighting practice, amateur contributors freely offer their “definitions” to the world for reuse and reinterpretation.¹ This open-source approach, where a multitude of designers take on a seemingly infinite number of conceptual and geometric challenges in a collaborative environment, seems to be optimal for exploring the tool. However, this initial period of design exploration must eventually lead to a more critical application in architecture, or risk falling into disuse. This thesis hopes to

¹ The Grasshopper for Rhino forum and the 3-D printing website Thingiverse.com are two good examples of this type of open-source technology sharing.
identify applicable uses of parametric design in architecture, and explore the elements that make them useful, in order to clarify a workflow that integrates parametrics fully into the design process.

Chapter 02 is an exploration of the historical foundations of parametric design and an inquiry into the fundamental basis for this approach. First, the origins of the term ‘parametric’ are examined and the meaning and intention of the term are investigated. Next, parametric algorithms are considered as systems – webs of interconnected elements with specified bounds. This leads to a look into the formal and geometric history of contemporary parametric design, particularly mathematical surface description. Next is a look at some of the founders of computational design and scripting, and their sequential, process-based approach. Finally, a critique of modern parametric approaches is considered, with an eye to when and where parametric tools are appropriate in the design process.

Chapter 03 considers parametric tools as a stylistic movement, as put forth by Patrick Schumacher and others. These designers believe that the critical Modernist tenet of “ornament as crime” is fundamentally flawed, and propose a new type of ornamentalism based on continuous forms and accentuated differences. This approach is supported by the research of Farshid Moussavi, whose book *The Function of Ornament* proposes that ornamentation – even in strictly modernist buildings – expresses concept and intention, and is therefore critical to architecture.

Chapter 04 examines a series of architectural precedents that utilize parametric design and digital fabrication at various levels and for different purposes. Each of three
pavilions discussed uses parametrics to investigate and further a concept, with excellent results.

Based on the research in the preceding chapters, Chapter 05 sets out a clear framework for implementing parametric tools in the design process, and introduces three projects that test the principles so far established. This begins with a division of parametric design into five distinct levels: Validation, Building Information Systems (BIM), Parametric Elements, Fully Parametric Description, and Generative Parametric Formfinding. The three most intensive levels here are each applied to a different project at a different scale: a lamp, a chair and a barn.

Chapter 06 investigates the process of designing a lamp using generative parametric formfinding. Starting from a concept and a material approach, a design is developed and fabricated. This includes defining the lamp in a fully parametric environment, then evaluating variations against a set of criteria. A final design is selected and fabricated using a combination of digital technology and manual techniques.

The chair design process outlined in Chapter 07 stems from a rethinking of conventional ergonomic principles and uses a fully parametric design process to maximize adjustability and fit. The design, a chair for a teacher, uses parametric tools to produce a flexible and repeatable chair type that encourages a variety of use positions. The fabrication approach – contoured, sectioned layering – acknowledges the limitations of CNC routers and uses that as a basis for fabrication.
The final project, outlined in Chapter 08, is a barn for two donkeys. This project applies parametrics in three distinct elements in the barn: a siting analysis, a structural system for a twisted roof, and a slatted skin system. Each element is considered as a distinct project within the larger context of the building, influencing and receiving influence from the barn as a whole.

Chapters 09 through 11 review the parametric design process and acknowledge trends between all three projects. Chapter 09 looks at the parametric process as a series of actions, and considers how the order and linearity of the process reveals strengths and weaknesses of parametric design. Chapter 10 acknowledges that parametric tools require designers to relinquish work to the computer to some degree, and asks how architects can maintain both freedom and control in this setting. This includes a look at where and when designers have direct control over the design, questioning the rhetoric that parametrics are beyond designer influence. Lastly, Chapter 11 investigates the effects that parametric design is having on labor both in the office and in the field, and discusses how parametric projects can actually enable workers and provide new jobs.
ORIGINS

Luigi Moretti’s 1960 booklet for his Milan exhibition entitled “Exhibition of parametric architecture and of mathematical and operational research in town-planning” is likely the first substantive use of the term “parametric” in architectural discourse. Moretti’s thesis revolves around the digestion of a design problem as an identifiable and quantifiable set of parameters, which are then subjected to a series of geometric equations to establish an idealized form. In the introduction, Moretti links his thesis to the advances in quantitative military analysis – called “Operational Research” – during World War II. Rather than use empirical data to determine the most effective methods for a particular type of operation, the military began establishing quantitative systems for determining ideal systems. Moretti gives the example of a plane trying to bomb a railway line:

A plane drops five bombs over a railway line; the five points were hit, they are alligned [sic], have a gaussian distribution around the target. The question calling for an answer concerns the best angle... the problem is solved by a very simple mathematical formula:

\[
\sin \phi = \frac{a}{d}
\]

in which \( \phi \) is the optimum angle between the course of the plane and the direction of the railway line, ‘a’ is the width of the target, and ‘d’ the intervals between the points where the bombs dropped. (Moretti 1960, 10)

Just as this represented a significant departure from the traditional methods of military strategy, Moretti’s use of parametrics in architecture is very novel, if underdeveloped.
His projects in the booklet deal primarily with optimizing a stadium for sight lines to the zones of greatest interest. He identifies the need for this type of analysis, noting that the difference in price of “the various zones of the seats of a stadium is a proof of the casual heterogeneousness of the service itself…” (Moretti, 12). As an alternative design method, he outlines a set of parameters that define the best possible perspectives, as well as a range of acceptable perspectives, and creates a field diagram (Figures 1-2). From this diagram, he generates a model of a seating arrangement (Figure 3). While these models and diagrams seem to relate only to visual parameters and therefore have little extensive application, a seed for the potential of parametric design lies buried in the rules he establishes.

![Figure 1: Geometric diagrams that define the visual requirements of a soccer stadium in mathematical parameters.](image)

2 Typical parameters for a swimming pool stadium include: “visibility of the whole pool;...comparatively low speed of the athletes in the water [resulting in] a visual field, physiologically bearable, up to 120°,” and so on.
Figure 2: Field diagrams describing “visual appetence” derived from the geometric principles established in Figure 1.

Figure 3: The resulting Stadium form.
Systems

An important field in architecture deeply connected to parametrics is the study of systems. While parametrics works to create new relationships between elements, systems thinking is an attempt to understand and harness the interrelationships already present in the world. In systems thinking, architects view a system as comprised of a set of interrelated parts, with inputs, processes, and outputs. Additionally, systems are subject to a conceptual Heisenberg Uncertainty Principle; a given system has different characteristics based on the perspective of the observer. Therefore, a crucial step in understanding a system is defining its bounds. Partitioning of systems also allows for interaction and grouping of separate systems in a larger system. This idea of ‘chunking’ – breaking a system into more manageable parts – is crucial to understanding systems.

In architecture, no one has put forth a more in depth analysis of this concept of chunking than architect and mathematician Christopher Alexander. In his 1964 book Notes on the Synthesis of Form, he writes,

> two minutes with a pencil on the back of an envelope lets us solve problems which we could not do in our heads if we tried for a hundred years. But at present we have no corresponding way of simplifying design problems for ourselves. [Notes on the Synthesis of Form describes] a way of representing design problems which does make them easier to solve. (Alexander 1968, 6)

The book presents an exhaustive approach to defining design problems and solving them mathematically. A crucial step in this process is to chunk the problem. Alexander writes, “…two requirements are linked if what you do about one of them in a design necessarily makes it more difficult or easier to do something about the other” (107). Full comprehension of this causal relationship between elements is fundamental to arriving
at a successful design understanding. Architect Mark Gross writes in his PhD thesis that “systematic problem decomposition, also known as ‘divide and conquer’ is no new idea. But its systematic application to design, and in particular to architectural design, was Alexander's contribution” (Gross 1986, 128).

If *Notes on Synthesis of Form* was Alexander’s polemic on the value of decompositional chunking in design, then his 1977 tomb *A Pattern Language* is the instruction manual and the user interface. Ordered into three sections for working at city, neighborhood and house scale, *A Pattern Language* takes the math out of the equations in *Notes*, and lays out in simple terms a network of instructions for designers and planners. Accompanying each set of instructions is a staunchly logical explanation of the problem as seen by Alexander and his colleagues, as well as the solution they propose. For each problem, Alexander names the concerns at hand, the possible tools – or *patterns* – to deal with the problem, and lays out a design approach. Each entry is also cross-referenced to a host of related topics. This is in many ways similar to Moretti’s approach, and reflects a parametric methodology, if much less formal in result. By defining a design problem as a set of parts, both architects were able to extract the essence from the problem and move systematically toward a solution.

Alexander’s *A Pattern Language* is considered by many to be damningly prescriptive. As an unadulterated tool for design, it does tend to result in fairly unremarkable forms. A quick look to one of Alexander’s architectural works – the Julian Street Inn, a homeless shelter in San Jose, California – reveals a somewhat referential architecture, what appears to be an updated take on Bavarian timber framing, with
ornate, curved beams overhead and heavy, masonry walls. Columns and pilasters support well proportioned capitals, and the whole building uses earthy, dark materials and colors (Figure 4). While well executed, this building in no way represents an architectural revolution. However, the theory that supports its modest form is broad and substantial.

Figure 4: Christopher Alexander’s Julian St. Inn, a homeless shelter in San Jose, California.

Alexander’s *A Pattern Language* is a thorough, investigative look into the places and spaces that work in architecture. Heralded as a truly research-based approach to architecture, the book is laid out into 253 ‘patterns,’ or solutions to problems that Alexander and his associates recognize in the built environment. Integral to the pattern system are the interconnections between patterns. Alexander writes,
no pattern is an isolated entity. Each pattern can exist in the world, only to the extent that is supported by other patterns: the larger patterns in which it is embedded, the patterns of the same size that surround it, and the smaller patterns which are embedded in it. (Alexander et al. 1977, xiii)

Further, he states, “when we use the network of a language, we always use it as a sequence, going through the patterns, moving always from the larger patterns to the smaller” (xviii). Each pattern, then, is a node, connected with a web-like system to other patterns, and in whole creating a working, distributed system.

This interrelation of the patterns is crucial to understanding Alexander’s approach. As a theorist, Alexander has identified a final goal: what he considers to be a whole world. The patterns then are possible approaches to this whole environment, and through their interconnectedness they establish a path. In addition to proposing rules of thumb for design and a stylistic vision of the final result (what Alexander would argue is a correlative byproduct of the patterns), A Pattern Language also offers a workflow for design. The process he proposes – of designing sequentially from the largest possible scale to the smallest, and compressing as many patterns as possible – is clearly laid out in the introduction. The book then is an instruction manual, replete with step-by-step instructions of how to achieve a desired result. Figure 5 is a diagrammatic representation of Alexander’s workflow.

____________________

3 In a theoretical sense, Alexander believes that “buildings work in the realm of feeling” (Alexander 1982). This approach stands in opposition to the modernist approach, where buildings are based on ideas and concepts. Alexander’s 1982 debate with Peter Eisenman provides excellent examples of the two theoretical approaches. The split here is one possible reason that Alexander’s work has been shunned by the architectural mainstream for the past 40 years.
The fact that *A Pattern Language* presents an adaptable, step-by-step approach to designing a building makes it a significant stepping-stone toward a parametric approach. Luigi Moretti’s parametric design system defines a problem, states the factors influencing it, then defines the relationships between those factors; similarly, Alexander is creating solutions to problems based on their fundamental definitions and the network of things that affect them. While Moretti remains largely in the domain of mathematics, however, Alexander ventures into an experiential view of the real world. If Moretti and the rest of contemporary parametric design work with the *created*, Alexander’s research focuses on the systems-thinking domain of the *observed*. Because it deals not just with elements but with whole, real systems, Alexander’s processes must be a stepping stone toward a holistic parametric approach to design.
Concurrent with the more mathematical approaches to incorporating parameters into design at a conceptual level, architects in the 20th century experimenting with freeform morphology found a key ally in the mathematics of surface creation. While the concepts for these forms were not derived from parameters, their shape was. Artist and architect Frederick Kiesler performed a series of experiments in freeform architecture. Of particular note is his 1958-59 exhibition “Endless House,” a free-flowing and amorphous structure on show at MoMA. The form of the house, Kiesler insists, “is not amorphous, not a free for all form. On the contrary, its construction has strict boundaries according to the scale of your living. Its shape and form are determined by inherent life processes” (Mical, 149). The relationship between the house’s form and these ‘life processes’ is unclear, but we can take Kiesler at his word.

Concurrent with Kiesler’s New York exhibition, Le Corbusier and his associate Iannis Xenakis prepared a pavilion for the 1958 Brussels World’s Fair Exposition that experimented heavily with mathematical surface creation. The structure, designed to house an interactive musical performance, is tent-like in form; the design focuses primarily on the interior acoustics. Xenakis created a set of drawings that show a clear relationship between the acoustic quality desired and the form of the building (Alvarado & Muñoz 2012, 109-111).
Architecture in the throes of Postmodernism was more concerned with image than form, and this shows in the architecture of the period. Beyond a few architects experimenting with curved forms, and some important advances in modular construction, parametric architecture took a brief rest in the 1970s and early 1980s. Technology and mathematics did not, however. Piérre Bezier’s crucial work in defining lines and surfaces – definitively published in his 1970 *Numerical control: mathematics and applications* – is the foundation for the Non-Uniform Rationalized B-Spline curve, or NURBS curve⁴. This system of defining curves based on a series of points with weights and degrees of influence is essential the design of curved surfaces, allowing designers to create surfaces using a set of coordinate points.

Drawing directly from Bezier’s work with curved surfaces, Frank Gehry has become the most famous proponent of the complex curve in architecture. His work, including the Guggenheim Museum in Bilbao Spain (Figure 6) and the Walt Disney Music Hall in Los Angeles, California, is synonymous with dynamic, complex form. The surfaces he creates are often *doubly curved* – concave or convex in both isometric directions – requiring complex mathematical definitions to make them reproducible and manufacturable. The individual components that make up a doubly curved surface must each be custom manufactured, and therefore each piece must be defined and indexed individually so that they fit together with as little tolerance as possible. To achieve this, 

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⁴ Bezier’s primary field of research was in the automotive industry. As an employee of Citroen, he designed some of the first truly curvilinear vehicles based on wind resistance tests. The forms he defined have become ubiquitous in the automotive industry, and their influence has spread to all fields of design.
Gehry’s firm utilized the software program CATIA from the aerospace industry, and developed their own scripts and algorithms for subdividing the larger surface into manufacturable components.

Figure 6: Frank Gehry's Guggenheim Bilbao was one of the first buildings to use mathematical algorithms to shape individual panelized elements.

**Contemporary Considerations**

While Gehry’s practice was building complex forms (at fantastic cost), a hard-core of designer-programmers were making important advances in programming to define even more complex form. The work done in the 1990’s and 2000’s by designers such as Jessie Reiser and Nanako Umemoto is notable in its complex handling of form and structure, as well as its process-based approach to design. Their firm Reiser+Umemoto published *An Atlas of Novel Tectonics* in 2006, a polemic on the use of complex, digitally derived form in architecture. The essence of their stance seems best
summed up in the statement that architecture should be based on "an and-and-and [system] - neither pure classical models, nor pure structural honesty nor pure compositional formalism, implying a more open-ended process” (27). As a firm they believe that architecture should not follow in the footsteps of others, should not be pure function, and should not be pure form. What lies between these grand typologies is of greatest interest (Figure 7). Their process involves several identifiable parts: investigating the inherent nature of materials and their preferred form; identifying and celebrating difference and variation within a field; and searching for "productive deviations from the minimal path” (176).

![Diagram of Atlas of Novel Tectonics in Perspective]

**Figure 7: Atlas of Novel Tectonics in relation to other movements.**

Particularly interesting is their approach to materials and field variation as design parameters. They approach materials not from an engineering standpoint - what can this material do - but from a research perspective: what does this material do? They look to the material for direction. For example, looking at a piece of wood, one sees
knots, variations in grain, and 'figuring,' or pattern. They would call these intensive characteristics, and celebrate the individual differences as well as the whole effect. They write: "mere quantity allows only for the quality of mere quantity. But intensive quantity generates a whole irreducible to the sum of its parts: in other words, a whole-whole relationship" (46). Secondly, in a subsequent example, the variations from location to location in that piece of wood could be analyzed and result in an optimized use, based on a field diagram. In other words, rather than using an ideal model of a piece of wood, adding a significant safety factor and designing for repetition, they are suggesting that as architects we should take each "piece of wood" on a case by case basis, analyze its strengths and weaknesses, and determine a use, either in an existing design or in a novel one (Figure 8).

![Reiser and Umemoto's Material Analysis](image)

Figure 8: An approach to thinking about materials.

*Atlas of Novel Tectonics* then is a framework for design, rather than a prescriptive set of parameters like *A Pattern Language*. As a framework, the book begs to be substantiated and tested in both theory and in form. Ideally, this means considering contemporary issues such as sustainability, cost and social impact, in
addition to material and form. However, this networked approach means that one can merely add parameters - nodes or vectors - and generate results. The type of parameter is unimportant as long as the data can be logically related. Reiser and Umemoto caution against the use of architecture as a social tool in the style of Le Corbusier, citing Michael Foucault: “’If one were to find a place, and perhaps there are some, where liberty is effectively practiced, one would find that it is not owing the order of objects, but once again, owing to the practice of liberty’” (55). This tautological warning doesn’t prohibit using architecture to better the lives of others, but warns that even great architecture will fail in this regard if the systems in place are not working properly. Properly applied, however, social concerns could certainly become parameters in a larger framework for identifying a design approach.

Reiser + Umemoto's work certainly displays examples of their "and-and-and" approach. Usually, this manifests in a novel interpretation of a traditional form. One of their first projects is a reinterpretation of the classical barrel vault. They first analyze the form and its purpose: an arch-based support structure that acts as a ceiling. This gets a functional and formal reconsideration. Second, they consider a pattern, the diamond lattice, and reinterpret it as a structural approach. Third, they apply a structural analysis of the resulting lattice mesh and allow variations to improve strength and provide intrigue. They kindly diagram this entire logical process for their readers (Figure 9), and the result (Figure 10) is not purely structural, not purely formal, and not purely traditional; it considers all three elements. In general, however, the concepts Reiser and Umemoto engender usually manifest in some sort of mesh skin or monocoque. Office
Da's Helios House gas station project follows a similar trajectory: a topological study of the column and lintel led to an amorphous canopy that combines supports, the pay kiosk and the pumps into column-like extractions. The structure in this case is concealed, but the concept remains valid. OMA’s Seattle Public Library is another example of a similar result, albeit reached from a completely different process. Notably, most of these projects tend to be mesh-based and curvilinear.

Figure 9: Reiser + Umemoto's diagrammed approach to form-finding.
Contemporary Criticism

In an interview in *From Control to Design* (2008), Sanford Kwinter and Jason Payne discuss the evolution of parametric design through three generations of architects, and consider the role that parametric tools will take in the future. Kwinter, an architectural theorist and critic, represents an older generation of designers and thinkers from the late 1980’s and 1990’s, while Payne is a contemporary designer wholly rooted in scripting and digital methods. The foundation of their discussion revolves around the type of architecture that employs “indexicality.” This term, as Payne describes, refers “at its most basic level to generating an organization by playing one system off another” (Ferré and Sakamoto 2008, 221). In this case, indexical architecture could also be called parametric architecture, in that the systems created are
interdependent and mathematically controlled using computer software. Kwinter and Payne go further to discuss what “Greg Lynn refers to... as ‘monstrous indexicality’” (Ferré and Sakamoto 2008, 221). This, Payne elaborates, is “work that makes a central point of indexing, where displaying the indexing motif has become an end in itself. This usually means that there is a visible reciprocity between the two (or more) systems” (Ferré and Sakamoto 2008, 221). Monstruous indexicality, then, is the application of a pattern to absurd levels of detail – a single surface composed of 3,000 parts, each different. The goal of these projects is to “produce compositions that, more than anything else, strive to be obviously indexical (or parametric, or scripted) in aspect. This work seeks to look as indexical as possible as if this were a virtue in itself” (Ferré and Sakamoto 2008, 222).

This overtly parametric approach to design seems doomed from the start by its very nature. Both Kwinter and Payne are highly critical, describing it as “stultifyingly routine,” “deliberately superficial,” and “one-dimensional literalism” (Ferré and Sakamoto 2008, 221-2). In that the goal of this type of work is to look as parametric as possible, the emphasis is not on buildability or a conceptual driver but on one’s ability to design it in a certain software and to represent it digitally. In other words, the pattern often precedes the architecture itself. This, I would contend, is the primary problem with this approach, and the reason Payne believes it to be “well on its way to having been exploited and exposed beyond public tolerance” (Ferré and Sakamoto 2008, 222). However, Payne identifies what he hopes to be a more fruitful application of parametric design. He lauds designers that use
indexing incidentally, simply to get the job done. Indexing to produce distinct effects, indexing to connect two different systems, etc. It’s use is more sparing and judicious, less naïve and therefore less glorified and totalizing. ‘Use when necessary and then move on’ type of thing. Very pragmatic. (Ferré and Sakamoto 2008, 222)

This approach does seem to yield much more more considered, less self-conscious designs.

The fundamental difference here is in the role of parametric tools in the design process; rather than a computerized definition or a pattern that precedes its function, the definitions here arise from a specified need. Just as an architect will develop initial ideas in hand sketches before transitioning to CAD software, a good parametric designer must have a clear set of intentions before ever beginning to program a definition or script.

This is a critical order of steps, based in large part on the precision of the tool. While CAD and parametric tools can give a design 100% accuracy, this is not always beneficial for the finished product, and certainly not for the design process. Working at a high level of precision from the beginning means that the composition becomes a patchwork of completed elements, risking disunion as a whole. A clear analogy comes from freehand drawing; artists always move from a low level of detail over the whole drawing rather than beginning in one corner and filling in the sheet with a final level of detail. This hierarchical approach is both a timesaver and an insurance against perspectival and contextual errors.

It is an important distinction that this approach does not preclude designing an entire building with parametric tools. The software itself is merely an instrument, highly capable of a specific result. If the project as initially conceived requires this sort of highly
computational differentiation from an early phase, then parametrics are the weapon of choice.
CHAPTER 3:  
PARAMETRICISM  

There is another contemporary school of thought, very much anathema to Kwinter’s (and many Modernist’s) understanding of effective architecture, which requires consideration. The resurgence of patterning in architecture, in large part as a result of the accessibility of articulated, responsive designs through parametrics, is an interesting challenge to the strict de-ornamentation prescribed by Adolf Loos and the 20th century Modernists. Patrick Schumacher, company director and senior designer at Zaha Hadid Architects, is arguably at the forefront of a growing movement in architecture that he labels Parametricism. Concerning the movement, Schumacher writes,

the key issues that avant-garde architecture and urbanism should be addressing can be summarized in the slogan: organising and articulating the increased complexity of post-fordist society. The task is to develop an architectural and urban repertoire that is geared up to create complex, polycentric urban and architectural fields which are densely layered and continuously differentiated. (2008)

This style, then, is named for a computerized approach, but its goals are decidedly not computerized. As the ability to create differentiated building elements becomes more generally accessible through the use of computerized machinery, it will be easier to avoid the trappings of Fordism – great economy, but inflexibility and homogeneity of product. With this new tactic for manufacturing, however, comes an infinitely wide field of options. Parametricism hopes to offer a playbook. They list an interesting set of heuristics, both positive and negative, outlined in Figure 11 below.
Patrik Schumacher’s Heuristics of Parametricism

**Negative heuristics:**
- avoid familiar typologies
- avoid platonic/hermetic objects
- avoid clear-cut zones/territories
- avoid repetition
- avoid straight lines
- avoid right angles
- avoid corners
- and most importantly: do not add or subtract without elaborate interarticulations.

**Positive heuristics:**
- interarticulate
- hybridize
- morph
- deterritorialize
- deform
- iterate
- use splines
- nurbs
- generative components
- script rather than model

Figure 11: The heuristics of Parametricism, from Patrick Schumacher’s 2008 lecture, “Parametricism as Style: Parametricist Manifesto.”

Perhaps the most emblematic of their diversion from Modernism and the proceeding styles is their insistence that architects “do not add or subtract without elaborate interarticulations” (Schumacher, 2008). This proposition is startling in its contrast with Modernist architectural thought. Schumacher is proposing an architecture where every inflection is smoothed, to provide interarticulation between moves.

Architecturally, this is a drastic diversion from Modernism. In *Towards a New Architecture*, Le Corbusier writes, “our eyes are constructed to enable us to see forms in light. Primary forms are beautiful forms because they can be clearly appreciated” (Conrads 1971, 59). Geometrically, this represents in his polemical Villa Savoye. The circle, the square and the line are Le Corbusier’s building blocks, and by using those elements and none other he constructs what is considered a pinnacle of Modernist design (Figure 12). A quick look at the architecture of Zaha Hadid Architects shows a very different approach; while a far cry from any traditional form, Hadid and
Schumacher are working to create buildings with no immediately classifiable forms whatsoever (Figure 13).

Figure 12: Le Corbusier’s Villa Savoie contrasts simple geometry, accentuating their difference.

Figure 13: Zaha Hadid's Heydar Aliyev Cultural Center in Baku, Azerbaijan uses non-primary geometry.
The language of the Parametricists’ proposal is also notable. It is nearly impossible to find any significant writing in Modernism that promotes anything elaborate. In his prophetic 1908 manifesto *Ornament as Crime*, Adolph Loos stated that “the evolution of culture is synonymous with the removal of ornament from utilitarian objects” (Conrads 1971, 20), which included buildings. If this statement was the basis for the stark, clean lines of modernism, then Parametricism represents a massive departure, even a return to traditional sensibilities. In an article in *Architectural Design*, Schumacher (2009) writes, “to oppose ornament/decoration to function would be a fallacy”. He adopts and reinterprets the three divisions of traditional architecture – *distribution, construction, decoration* – as his terms *organization* and *articulation* (Schumacher 2009). Articulation in his case involves the employment of patterns and decoration, but to accentuate inflections and differences in the architecture.

It is interesting to consider briefly the role of Parametricism as it exists now, in opposition to the dominant architectural style of Modernism. As Modernism came into popularity with the architectural avant-garde of Europe in the 1910’s and 1920’s, the dominant architectural style for most structures remained firmly with the Beaux-Arts school of design. Beaux-Arts architects rejected Modernism as too dull and lacking visual interest, while the Modernists considered (and still consider) Beaux-Arts design to be overly ornate and referential. At the time, Beaux-Arts was the dominant school of thought. Conversely, when Sanford Kwinter – a Modernist – refers to Parametricism for its own sake as “deliberately superficial,” he speaks from the dominant architectural school of thought (Ferré and Sakamoto 2008, 221). The subversive in architecture is now
the ornate, subject to intense criticism from the staunch Modernist mainstream. The parallels between the Parametricist agenda now and the Modernist one of 90 years ago are fascinating.

If we then accept pattern as a way of accentuating differences in architecture, how does it manifest tectonically? One position that runs parallel to Schumacher’s is that espoused by Farshid Moussavi, co-founder of Foreign Office Architects and founder of Farshid Moussavi Architects. In collaboration with Michael Kubo in 2006, Moussavi edited *The Function of Ornament* – an exhaustive exploration of the different types of ornament in Modernist and contemporary design. In the book’s introduction, Moussavi defines ornament as

> the figure that emerges from the material substrate, the expression of embedded forces through processes of construction, assembly and growth. It is through ornament that material transmits affects. Ornament is therefore necessary and inseparable from the object... It has no intention to decorate, and there is in it no hidden meaning. (Moussavi and Kubo 2006, 8)

Moussavi is referring specifically here to the Deleuzian use of the term *affect* – “the ability to affect” (Deleuze 1980, xvi), as a way for architecture to “render the invisible forces in contemporary culture visible” (Moussavi and Kubo 2006, 8). This framework becomes evident in the examples in *The Function of Ornament*. Each entry has a title for its affect, ranging from ‘fluted’ to ‘scaleless’ to ‘branded.’ The book then demonstrates through drawings and diagrams how each project achieves its particular affect. The book in excels as an architectural resource, but embedded in the entries is a firm belief that ornament as described here has a clear place in architecture.
Consider briefly the dichotomy between form and function in design. Moussavi and Kubo insist that ornament has a function, and Postmodernists Robert Venturi, Denise Scott Brown and Steven Izenour insisted in *Learning From Las Vegas* (1977) that in buildings “where the architectural systems of space, structure and program are submerged and distorted by an overall form” (what they refer to as *ducks*), the “building... is a symbol” (88). Bypassing the valuations in the Postmodernists’ argument, we can conclude that abstract geometric form is in fact ornament. The question then arises: what makes an element functional, and not purely formal? There are myriad projects where a strictly formal concept or tectonic led to a building design, and while the results may be beautiful and astoundingly complex, they can sometimes lack conceptual clarity. It may be argued that the tools of complexity – scripting, Grasshopper, etc – have arrived ahead of their fitting application (as many great inventions do). In hoping to establish a place for parametrics in design, it is important to look to successful precedents. The three pavilions discussed below – the Endesa Pavilion in Barcelona, Spain by the Institute for advanced architecture of Catalonia; the 2005 Serpentine Gallery Pavilion by Álvaro Siza, Eduardo Soto de Moura and Cecil Balmond; and the Boston Harbor Islands Pavilion by Utile – are examples of when the tool is harnessed for the benefit of a concept, rather than vice versa. The Endesa Pavilion is an example of the true integration of a parametric tool into the very design of a building, but with an ecological rather than formal intent. In the Serpentine Gallery Pavilion, the inherently parametric aspects of the design seem to serve the greater programmatic
and conceptual aspects and through their simplicity give the project a humble character.

Lastly, the Boston Harbor Islands Pavilion demonstrates clearly how an approach toward digital fabrication can be integrated into the initial design, but the final construction process can be an echo of that fabrication process. In all three cases, the parametric aspect is a means to a greater end.

**Endesa Pavilion**

At the cutting edge of parametric design research is Spain’s Institute for advanced architecture of Catalonia (IaaC). The Institute produces an experimental building annually to showcase the work of faculty and students and to prophesize the future direction of architecture. Their 2013 project, the Endesa Pavilion, is one of the best examples of systemic parametric design to date (Figure 14). The project is located on the Marina Dock in Barcelona, several hundred feet from a series of buildings designed by Frank Gehry in preparation for the 1992 Summer Olympics.⁵ This architecturally significant setting provides the backdrop for an experiment in form, fabrication and parametrics.

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⁵ Gehry’s project included the ‘Fish’, considered by many to be the first large-scale indexed, panelized architecture project.
The building itself is both a physical polemic for the IaaC and a functional space. Designed as a classroom and a control center for the Smart Cities Expo’s Smart Grid studies, the temporary structure is a reflection of its Mediterranean habitat. The design is specific to a warm, dry climate: the exterior is unfinished Oriented Strand Board (OSB), and the pinecone-like exterior (Figure 15) gives the building a substantial surface area, largely un-insulated. For Barcelona, however, the adaptations are beneficial: the same “solar bricks” along the exterior create large overhangs to shade windows and exterior spaces.
The “solar bricks” are the core of the project. Projecting various distances and at various angles, the triangular appendages give the building a decidedly ‘parametric’ feel. However, far from being random in angle or proportion, the bricks are carefully calculated based on sun angle, position, and function of the adjacent interior zone (Figure 16). Atop each brick along the two elevations with southern exposure sits a solar array. The building design uses a parametric system to calculate the sun angle, exposure and required energy loads throughout the day, and rotates the bricks accordingly. On the exterior, this results in a bristling, almost unfriendly appearance. On the interior, the cavities inside the bricks create storage and somewhat dubious lounging spaces, resulting in a lively interior elevation (Figure 4).
The scale of the bricks relative to the whole is what makes this project formally unique. Whereas most projects utilizing parametric tools tend to use smaller unit or component sizes to achieve a more fluid composition, this project seems to recognize convention in material sizes. The result is that “the Endesa pavilion is an accessible device, technologically soft and easily understandable. Its construction, materials and
energy, and its climatic behaviour are transparent to the inhabitant” (Rubio 2011, 8). This transparency is clear from photographs: the structure is exposed on the interior, and the unfinished plywood surfaces lend an honest feel. The tectonic is immediately apparent: irregularly spaced columns support a flat roof, and the solar bricks fill the column bays. It is the scale of the bricks, however, that gives a playful, humanist feel to the structure. At that scale, the overall appearance is understandable, not unapproachable. The whole building seems to be something any deliberate carpenter could assemble.

The actual manufacturing process is not immediately obvious, however; all the solar blocks were cut precisely using CNC tools and constructed offsite. Writes architect Rodrigo Rubio (2011), “digital fabrication techniques are applied to speed up construction times. Each piece is coded. Assembly process is just like solving a real scale 3d puzzle” (9). This departure from the traditional, craft-based approach to construction means that the project has great potential for accuracy and reproducibility, and the control of manufacturing lies in the hands of the architect. However, while large construction companies may be able to afford this sort of CNC manufacturing, its implementation at a small commercial scale is unrealistic at this time. The result is a project that looks like it was built by a carpenter, but in reality requires expensive tools to build.
Serpentine Gallery Pavilion

If the Endesa Pavilion is an example of an effective application of parametric tools to the skin of a building, then the 2005 Serpentine Gallery Pavilion in Kensington Gardens was its structural equivalent. The pavilion, designed by Álvaro Siza, Eduardo Soto de Moura and Cecil Balmond, was a temporary exhibition for several months in 2005 (Figure 18). The building, writes Guardian architectural critic Steve Rose (2005) is surprisingly simple:

A café by day and a venue for talks and events at night, it is little more than a grid made from short planks of timber, folded down at the edges to form the walls. Panes of polycarbonate fill in the squares of the grid until it meets the ground on extended "legs". Anyone with a basic knowledge of woodwork will be able to see immediately how it's been put together: with mortise and tenon joints. A bolt secures each joint and there's your pavilion.

This structural system (Figure 19) is stunning in its simplicity. Each piece requires only a few cuts, although each is unique. No piece is larger than two bays, or about 8 feet. Assembled, however, they create a beautiful and functional form that promotes the formal and conceptual aspects of the architecture rather than overwhelming them. The walls of a rectangular box curve inward to dodge two massive oak trees and open to accept a path passing through the pavilion. Seemingly in response, the roof buckles upward, creating a shallow vault that flattens toward the Serpentine Gallery (Figure 20). From eye-level, the structure seems surprisingly modest, and the tone and materials further enhance that sensation. The overall effect is far from jaw-dropping; just as Siza, Souta De Mouro and Balmond intended.
Figure 18: The 2005 Serpentine Gallery Pavilion, by Alvaro Siza, Eduardo Soto de Moura and Cecil Balmond. (serpentinegallery.org, 2013).

Figure 19: The pavilion’s structural system. Short members intersect each other at midspan (Architectural Design No 6, 2005).
The true importance of this structure lies in that effortless feeling. Far from looking like the massive engineering effort it was, the pavilion looks fairly simple. And in essence, it is. There is only one type of joint, and all the components are relatively manageable in size. Just as the Endesa Pavilion could be a substantial summer project for an accomplished woodworker, the Serpentine Gallery Pavilion is equally manageable and “technologically soft.” In fact, with access to the required software and a CNC router, a project such as this would pose little technical difficulty. And that simplicity shows; in adapting a vernacular joinery method – the mortise and tenon – and a vernacular material – wood – the architects have created an accessible structure, aware of its surroundings, and responsive to site and programmatic forces. The highly technical, parametric aspects of the project complement the overall effect, rather than
steal the show. As Hugh Pearman (2005) wrote in a review of the pavilion: “This is high tech that looks anything but high tech”.

In fact, the application of this technology in other types of construction is promising. Using this sort of algorithm to create curved surfaces from short lengths of wood is materially efficient. This system could act as a framework for a ceiling structure, with space for insulation and a consistent nailing surface. While at this time it seems unthinkable to cover such a structure with gypsum, its application as a useful structural system may supersede its raw appearance, in much the same way as conventional timber framing techniques.

**Boston Harbor Islands Pavilion**

Since most full-scale digital fabrication tools work best with inexpensive, flat stock, it is unusual to see an applied project that utilizes other materials. However, the process of forming is unique in that the final material is distinct from the formwork, separating the material constraints of the finished work from those of the initial fabrication process. This disconnect means that relatively low-grade formwork materials can be used to create a high-finish product. Since the materials used to create conventional, non-parametric formwork is equally low-grade, the only input increases are in the design and construction phases. Materially, a parametric product can be built with very little waste compared to a more traditionally orthogonal design.

One excellent example of a digital-fabrication forming project – realized at full scale – is the Boston Harbor Islands Pavilion (2011) in Boston, MA (Figure 21). Boston
firm Utile designed this three-season pavilion for the Boston Harbor Alliance and the National Park Service to create a visitor information pavilion to increase awareness about the archipelago. The pavilion was the first permanent structure to be located on Boston’s Rose Kennedy Greenway, the park above the section of Interstate 93 that was routed underground during the Big Dig. Since the program description only required protection from the elements overhead, the design focuses on the two doubly curved, thin concrete roof structures. The roofs collect rainwater and funnel it from the upper to the lower roof, then into a catchment basin to the south. This processional collection of water (that ends its journey as irrigation for the pavilion landscaping) is aided by the careful shaping of the roof structure.

Figure 21: Utile's Boston Harbor Islands Pavilion in Boston, Massachusetts.
In collaboration with engineering firm Simpson Gumpertz and Heger, Inc, a Rhinoceros model was used to design the surfaces that govern the roof. The designers fabricated a scale model of the structure to test rainwater runoff using ball Bearings. In an interview with Branden Klayko for The Architect’s Newspaper blog, Utile principal Tim Love said that designers “realized in modeling the pavilion that the water would ‘prefer’ to follow the same axis through both pavilion roofs... Turning the curve would have created unintended consequences in the flow of the water” (Klayko 2013). To design the formwork, the surface of the slabs was carefully divided into roughly rectangular panels, and a series of contouring ribs were extracted from the digital model to support the panels and hold them in place. For the spouts, where the curvature exceeded the tolerances possible using sheets of plywood, the whole panel was sliced into sections, cut from fiberboard, laminated and sanded smooth (Figure 22). All the formwork was cut offsite using a CNC router, and assembled quickly on location. The concrete itself, which thins toward the edges down to 3.5 inches, was carefully engineered through a testing process to insure both strength and a smooth surface (Klayko 2013).
From a final surface design, the architects extracted a series of curves along the surface to generate the steel support beams. These beams, said Love, offer “enough repetition that they began to look like contour lines... They allow you to more easily read the curve of the slab” (Klayko, 2013). The beams split as they approach the more heavily curved center of the roof structure and resplice on the other side, drawing attention to the curve and providing additional support.

The Boston Harbor Islands Pavilion is notable as a built example of a ‘file-to-factory’ project. Designers utilized digital design software, then directly transitioned into a fabrication design, outputting the files into a CNC interface for manufacture. The
formwork pieces were then cut using a router and the steel beams with a laser cutter. A coding system allowed for quick on-site assembly. Although some aspects of the design were laid out using traditional manual techniques, the majority of the project utilized digital processes both for design and manufacture. The design process didn’t utilize parametric software directly, but it is useful as a digital manufacturing precedent.
CHAPTER 5:  
PROJECT FRAMEWORK

Based on these precedents and the historical and philosophical underpinnings explored in the previous chapters, several trends for successful parametric integration arise. First, it becomes clear that parametrics should be driven by a concept. Kwinter and Payne both agree that parametrics in architectural applications are best suited to achieving a specific goal, and Reiser and Umemoto also insist on a conceptual basis for projects. The three pavilions examined in Chapter 04 all began with a concept, and parametrics are merely tools for achieving that concept.

Second, it is also clear that parametrics can play different types of roles in the design process. This can vary from a mere check or evaluation of an existing design to a fully parametric definition, where all elements are linked and related. Understanding these various levels is the first step to applying parametrics effectively. To do this, this thesis names five theoretical levels of integration. To better understand the ramifications of each, design projects were undertaken for the most complex integrative approaches.

These five levels stem from observations of applications in the field (precedents) and the author’s own work with various software programs. They represent a proposed hierarchy based on complexity of process and duration and timing of integration. There is extensive literature regarding the implementation of the various levels described here, particularly in the more commercially accepted approaches such as Building Information Management. Willis and Woodward (2010) identify three categories of
technological advances that they relate to computational design: building information modeling, parametric modeling, and mass customization (182). Further, they write that parametric models leave aside the qualitative and unmeasurable things considered by architects during the design process that make for a complete work of architecture... this is why parametric models are not yet used to design buildings, but instead to design parts of buildings. (188)

If the conversation is focused directly on the design process, rolling mass customization and fabrication into a separate (but inextricable) category, then a categorization begins to emerge. This document posits that new categorization (below) in the context of this thesis, admitting that its applicability to the wider world of architecture demands a critical review.

Levels of Integration

This thesis proposes that there are five levels of parametric integration that are variously applicable to an architectural project, depending on budget, desired formal strategy, and available expertise. In theory, as parametric design becomes more broadly adapted into practice, the more intensive levels will become applicable to a broader range of projects. The levels are outlined in relation to each other in.
Validation

At the lowest level of integration, parametric tools are used to evaluate and validate a pre-existing design for a variety of desired factors. These could include wind force behavior, solar gain and orientation, traffic patterns, acoustic performance and energy efficiency. While more broadly applicable parametric tools such as Grasshopper can be used to measure these factors, more specific tools such as Autodesk's Project Vasari, eQUEST and Ecotect are designed specifically to measure these sorts of factors. These for the most part are not formal parametric design tools, but instead are useful for quickly testing various aspects of the design, including window type and location, insulation type, wall thickness, and orientation. The information garnered from these analyses can lead to an informed design solution, but on their own they are not directly linked to a building solution. In essence, these softwares act as tests of specific building elements, but don’t actually change the design itself. Specification of window and insulation types are typical outputs of this sort of software process.
Building Information Management (BIM)

At the second level of parametric design, the software allows linkable objects and elements, so that the building can automatically update with broader design changes. This type of parametric design, typified by Building Information Management (BIM) tools, is becoming broadly adapted in architecture firms as a way of both saving time in drafting and to some extent in design. Discrete elements such as doors and windows can be specified in chunks so that any schedule-level changes don’t require redrafting. In addition, the designs can be specified to particular model numbers, so that the transition from design to fabrication to assembly is more or less seamless. Information can be cross-referenced from drawing to schedule with ease, and changes to a model overall propagate through all the sheets in the model. This type of workflow is parametric in that the model does in fact represent a networked series of elements, all dependent on each other. BIM systems fall short, however, in that the elements that can be created are more or less limited, as are the relationships between them. Proportion, placement and type are all indicated individually for every instance, and with the tools currently available, it is not yet possible to create a linked gradient of elements. While these tools are extremely useful for generating drawings quickly and accurately, they fall short as a design tool, tending to produce formulaic designs based on pre-packaged components and details. Additionally, the information-intensive approaches these tools require make them clumsy for initial design. Broad changes to the form of the building invalidate the internal data and previous relationships, making
design changes increasingly difficult as the project progresses. Many firms have found that a transition from a less information-intensive parametric modeling tool in the initial stages to a BIM system for documentation provides a useful blend of initial design flexibility and deep information integration. CASE, inc. – a New-York-based architectural consulting agency – has developed software plugins specifically for this type of workflow, making the transition as seamless as possible.

**Parametric Elements**

In the third level of parametric design, a discrete element of a building such as a façade or staircase is fully parametric, inhabiting a non-parametric building and adapting to the final form as necessary. This discrete parametric element inhabits the building as a “site,” adapting to the changing design as necessary. Variation can be continuous within the element, and parameters can derive from the surrounding building, the environment, and independently. In contemporary architecture, most uses of parametric tools fall into this category. Brooklyn-based firm Marble Fairbanks is particularly adept at this approach to design. Many of their projects conform a parametric element to a traditionally designed structure or existing building. The Slide Library at Columbia University is a good example; the Department of Art History and Archaeology needed to relocate its slide resources to a small, interior space, but with a prominent and well-defined position in the department. Marble Fairbanks created a simple rectangular space with four partitions, but utilized a parametric, digitally fabricated approach to activate the space conceptually and visually. One wall of the
room is a contoured mass with various apertures created by the oppositional folding of the interior and exterior surfaces. Where the surfaces fold past each other, layers of glass create visual connections between interior and exterior space, and draw a connection to the way light passes through a slide projector. The wall also bends outwards to capture sunlight for the hallway from a large skylight in the central space. A sectioned and contoured approach was used, with built-up layers of MDF carved to match edge conditions and create form. This parametric element is both aware of its surroundings and conceptually rich. An additional goal for the project was to highlight the digitally fabricated nature of the project. As such, the other three walls of the Slide Library are MDF sheets perforated with the outlines of the individual rib elements and laminated between translucent sheets of linoleum. These walls lend light to the hallway and draw the connection between process and result. The entire structure sits within an existing space, parameterizing and adapting to its surroundings. However, as with other discrete parametric element projects, the Slide Library does not shape the surrounding building, and the extents of the parametric design here are clearly limited to the element itself.

**Fully Parametric Description**

In a fourth level of parametric design, the boundaries between elements disappear, so that a connection is forged between all elements in a building. While documentation may be performed using traditional CAD workflows, the design process at this level demands a complete parametric digital model, so that all the elements are
linked. This allows visual and performance-based indexing throughout the building, but also insures that relationships between various elements are intentional. With these clear and direct connections, the traditional boundaries between elements can blur, allowing increased design flexibility. This holistic parametric approach is most often found in smaller, installation-type projects, although a few larger scale examples do exist. A totally parametric project requires intensive planning and coordination, but the results can be dramatic, with buildings that feel entirely integrated. Zaha Hadid Architects is probably the most prominent proponent of this sort of project approach. Hadid’s projects function in primarily formal territory, but they are remarkable as feats of digital engineering. The forms are often nearly seamless and defy structural expression, but always accent differentiation, so that the complexity of the forms are manifest in their appearance. This sort of complexity is only possible through the implementation of parametric tools at a holistic scale. While documentation of Hadid’s design process is notably scant, the structure, skin and systems of her buildings are all “continuously differentiated,” demanding a parametric approach. With most of her buildings this manifests as a fully customized structural system with each unique structural component separately designed and manufactured, as well as a panelized skin with individual panels meeting in contiguous edge conditions. Alternately, these two elements combine into a single structural shell, usually cast in concrete from parametrically defined formwork. In all cases, the emphasis is on not just using parametric tools, but accenting their use in the design.
Generative Formfinding

In the fifth and final level of parametric design, the parametric definition – not the final structure – is the subject of design. This largely theoretical field of parametric design uses form-finding and genetic solving to create a best-fit design, based on variable parameters with bounds and relationships set by the designer. It is unique in that the exact form for the building is not drawn by the architect, but “naturally” selected from a vast array of possible designs. Optimal designs based on a set of optimization goals are placed on a Pareto curve, where each design is rated equally based on multiple valuation systems. The variation in these individual designs can be infinite, but they are all considered equal. The designer’s final task is to select a final, optimal design from those on the Pareto curve. The decision to select a final model is arbitrary to the computer software, but allows the designer a final moment for subjective input. This step can seem unintuitive in an otherwise strictly defined digital process. To a lesser degree and for specific components, this sort of form-finding is already employed by many large firms to optimize façades and structures. There are no large-scale built examples of this sort of all-in, digital approach, but a number of research projects exist. Notably, former Architectural Association students Sean Ahlquist and Moritz Fleischmann (2008) wrote a paper on parametric formfinding as part of an Emergent Technologies seminar. The subject of their final project was an urban spatial envelope based on zoning regulations. The researchers developed an algorithm that used a rotating section plane to consecutively subdivide the envelope into programmatic spaces based on random angles and movements that generated volumes
of the desired size. The algorithm generated a number of designs, and a final design was selected for its particular form (Figure 24). While never constructed, the project is significant in that it represents a completely digital design process.

![Image](image.png)

Figure 24: Ahlquist and Fleischmann's 2008 exploration into generative formfinding in architecture resulted in a building envelope.

**Initiating a Parametric Approach**

To test the framework established above, three projects were undertaken utilizing various levels of integration and at three distinct scales or intensities. The specific projects were selected both because they represent clearly delineated objects at a scale that can be fabricated within the available timeframe, and because they offer various levels of complexity in terms of program and composition. The three projects
involved the parametric design of three discrete objects: a lamp, a chair and a small barn for two donkeys.

The lamp project represents the most basic level of design involvement. There are only two ‘site’ constraints to the project: it must support itself and emit light. The openness and simplicity of these design constraints lend the lamp to a highly experimental design process with complex fabrication requirements. The lamp was therefore designed using the highest level of parametric integration – generative parametric formfinding.

With the chair project, the complexity of the design constraints increases with the introduction of a human element. These new constraints include structural requirements and the more subjective criteria of comfort, ergonomics and functionality. The transition to a client-based design process, including specific ‘program,’ moves the design process a step closer to an architectural project. This incremental change in complexity helps identify the challenges inherent in a parametric design process. Additionally, the fourth level of parametric design – fully parametric form – was utilized to reduce the complexity of the parametric element of the project. The project was simple enough to allow design flexibility in a fully parametric environment, while still providing ample design constraints in an architectural environment.

Finally, the barn project provided a small-scale architectural project in which the bounds are constrained enough to allow for full or partial parametric design and fabrication in a real-world context. This complete design project marries parametric methods to real-world project requirements. As such, the design was developed to
integrate discrete parametric elements, which fit into a conventionally designed project.

Documentation was a mix of standard drawings and parametric ‘assembly instructions.’
CHAPTER 6:
LIGHT SKIPPER LAMP

Concept

The inspiration for the Light Skipper Lamp came from an investigation of a particular type of light, present in areas with deep contours and steeply slanted light, such as desert canyons, sand dunes at sunset, and certain interior conditions, such as those present in the Light Walls House in Tokyo by local studio mA-style Architects (Figure 25). These conditions present some of the most striking light conditions, and seemed like rich conceptual fodder for a lamp design.

Figure 25: mA-style Architects' Light Walls House explores the concept of oblique light falling on a textured surface.
Investigation of the images and the conditions that result in this “dappled surface” effect led to the realization that not only the light source but the surface it hit would have to be carefully controlled. As a result, the design became quickly dominated by a large shade to receive the light from a single source. Three major characteristics of the surface were isolated as having a bearing on the resulting light pattern:

- Surface Roughness
- Surface Contour
- Angle of Light

Modifying these characteristics to get the most visually rich light became the basis for design.

If these characteristics are the variables or genes of each lamp, then an evolutionary fitness measure is required to evaluate individual lamp gene combinations. As the desired result is a highly contoured surface with small pools of light and darkness, the following characteristics were measured:

- Number of Discrete Pools of Light
- Overall Surface Roughness
- Lit vs. Unlit Percentage of Surface Area

The first and second criteria were maximized, while the last criterion was set to approach 50%. Quantification of each fitness measure is covered below.

The next task was to narrow the design field. A series of categorical selections were made to facilitate execution of the concept, as shown in (Figure 26). The major categories for selection included:
Each category was evaluated for its effect on the character of the light, and the best option was chosen. A freestanding table lamp typology was selected to maintain the independence of the light over its surroundings. A translucent material was selected to allow indirect viewing of the light striking the shade. Based on the shade material selection – lightweight paper – an LED bulb was chosen for its low heat output, and so forth.

These design selections led to a basic parametric description of the lamp shape.

An unobtrusive base supports a lightweight shade that undulates both in large-scale shifts and in smaller undulations. The overall shape is based on radial displacement of several control points at five heights. Each control point can move inward or outward
independently, resulting in a change in the overall form of the surface (Figure 27).

Additionally, the bottom points can move vertically, creating an uneven base to the shade. That shape is matched in the base and offset inward to emphasize the shade. The pattering for the small undulations arises out of a mathematical formula for modeling water droplets, in a reference to the hydrologic forces that shape desert canyons. The formula produces a three-dimensional surface that undulates from a central point and gradually decreases in frequency and amplitude (Figure 28). This surface was then remapped onto the shade to create small-scale ripples. In addition to controlling the shape and surface of the shade, the height of the bulb was variable, allowing for many configurations. These parameters became the genetic basis for an evolutionary fitness algorithm to solve for the fitness criteria above.

Figure 27: Diagram of the controls over the lamp form.
Figure 28: This formula creates a dissipating ripple centered on a point.

**Measurement and Evaluation**

Parametric tools allow for nearly infinite variations, even within a very directed design field such as the one described here. In order to evaluate as many of those options as possible very quickly, an algorithmic solver was employed. While Galapagos – the native evolutionary solver for Grasshopper – is an effective and fast solver, this application required the implementation of multiple fitness parameters. Octopus is a plug-in for Grasshopper that can evaluate an individual against up to six fitness parameters (). Each individual is measured and placed in a multi-dimensional fitness landscape. Against a single fitness measure, there will be a single most fit individual. However, as elucidated by early 20th century economist Vilfredo Pareto in his essential work on Pareto efficiency, if multiple fitness values must be met, then there will almost always be multiple evolutionarily equivalent options. Pareto used the example of a
factory that can produce two goods, both of which are in demand, but is limited by the number of hours it can operate. If the factory operates any less than 24 hours a day, it is not running optimally. However, once it is running for all those hours, management must decide how to allocate them between Good 1 and Good 2. Assuming perfect market conditions, production choices varying from producing only Good 1 to producing only Good 2 and any combination of the two are economically equivalent. All these choices fall on what is referred to as a Pareto frontier, where all choices are different but equally good. Extrapolated into multiple dimensions, the Pareto frontier takes on a roughly hyperbolic form (Figure 30). Octopus not only measures all the individual genomes and compares them, but also identifies the most fit individuals – those on the Pareto frontier - and pre-selects them for the user.

Figure 29: Octopus is a multi-dimensional evolutionary solver that compares many individuals against multiple criteria.
To evaluate each individual lamp option, a quantification of each fitness criterion was required. To do this, a model of the way light casts on the surface of the lamp was developed. The best and fastest option was a meshing strategy that analyzed a triangulated representation of the shade. The bulb was modeled as a point source light, and a ray was directed from the point to each mesh face. All the faces that were obscured by other parts of the mesh were filtered into a “shaded” set, and those with a direct ray to the light point were filtered into a “lit” set. While the real lighting of each of these areas is far more complex because of material translucency, this offered a simplified measure. All adjacent panels were joined into “pools” of light and darkness, and the total area of the surface was compared to the area of lit portions. This provided the measurements for the Number of Discrete Pools of Light and Lit vs. Unlit Percentage of Surface Area. Overall Surface Roughness was measured as a variation in total surface area of the remapped surface from the original. More rough surfaces with larger
numbers of deep grooves resulted in a higher difference in surface area than smoother variations.

Finally, all the variable parameters were connected to Octopus, as were the fitness criteria, and the algorithm was allowed to run for a number of hours. Producing one new iteration – including mesh lighting analysis – every 2 seconds or so, a 6-hour run resulted in approximately 10,000 individuals. These were grouped into “generations” of 200 individuals, and the values of the top 10% of each generation were preserved in some of the individuals in the next. This allows the software to “learn,” discovering what combination of values works best and testing values near to those. After those 50 generations, the Pareto frontier consisted of 24 individual lamps, all fairly similar in appearance but with subtle variations in texture and form.

Selecting a Winner

Confronted with the field of 24 equivalent individuals (Figure 31), the author entered an unexpected and somewhat challenging phase of design. Assuming that each of the lamps presented is mathematically equivalent, achieving the desired effect equally, how can one select a single option for construction? The intent of the designer is encapsulated into the original parametric definition. However, the intuitive design sense of the designer is not limited to that same definition. While the limits to the basic form and strategy do represent an intuitive process, the software defines the actual form itself. This final selection step does offer another opportunity for the influence of intuition. Designers don’t like to consider that at some point they make decisions
because they “feel” right, but in fact the design process is littered with intuitive design decisions, from window placement to doorknob selection. These decisions separate the products of different designers, and give projects their integrity and soul. In the face of all the intuitive design decisions in a conventional design process, this selection of one evolutionary equivalent over another is relatively minor. However, it is not blended with other design decisions and situational interpretations, and therefore the subjectivity is immediately evident. The final lamp design here was chosen for its formal composition and proportion, as well as a good mix of valley and ridge shapes and depths: factors the algorithm was not set to optimize.

Figure 31: After Octopus solves for the optimal individuals, the designer is faced with a field of 'equals'.

Fabrication

Once a winner was selected, the lampshade was split into nine sections based on a maximum variation in offset of 1.75 inches. This value was derived from the two-inch thickness of the foam stock, and insured that each section could be milled from a single
thickness sheet of material. The surfaces were also converted to solids to the exterior of the shade (outside the mold) to allow for physical manufacturing. Each section was then reoriented flat onto the XY plane and baked into Rhino, signaling the end of parametric tools for this project. The plugin RhinoCAM was used to generate milling paths for the surfaces, and they were exported to a CNC router (Figure 32). Once cut, the nine sections were reassembled using adhesive into three larger parts. These three parts were assembled into a single mold with pins and a string wrapped around the exterior, and the interior mold surface was painted with a coat of acrylic primer and a coat of high-gloss, oil-based polyurethane to create a non-stick surface. Once cured, strips of Japanese calligraphy paper coated in a non-toxic, water-based adhesive were applied to the interior surface of the mold, overlapping as necessary to cover the entire surface. The strips were pushed by hand into the cavities created by the surface variations, then smoothed with a chip brush coated in adhesive. This system, developed through trial and error, allowed the paper to conform well to the variations in surface. Two layers of paper were applied in a single round, and the lamp was allowed to air dry for 24 hours. Once dry, strips extending beyond the top and bottom of the mold were trimmed, the three mold parts were removed and the lampshade was released (Figure 33).
Figure 32: The sections of the lamp mold being cut by a CNC router.

Figure 33: The mold was used to form pasted calligraphy paper, then removed.
The base, constructed from a solid piece of clear grain poplar, was also cut on the CNC router (Figure 34). The top surface is contoured in conversation with the base of the shade, and rises and falls to meet the bottom edge. The original design included a set of vertical ribs to cast shadow on the walls of the lampshade, so slots for these ribs were routed as well. Once assembled, however, the ribs proved too busy, and were omitted from the final design. A cavity routed from the underside of the base holds the wires for the lamp, and a slot allows the electrical wire to exit in one direction. Once removed from its stock, holes were drilled into the sides of the base at even intervals to receive pegs for support of the shade.

Figure 34: Routing the base from poplar.
The final lamp (Figure 35) stands freely on a table, and the resultant lighting is very close to that modeled in Grasshopper. After the lamp had been produced, it became apparent that the design is likely better suited to a hanging application, as the base and mounting system didn’t contribute to the overall composition. Additionally, the flared top of the lamp makes its application limited, as the bulb is directly visible from above. However, this was a successful exercise in parametric formfinding. A concept was executed to complete fabrication using parametric tools for nearly every step.

Figure 35: The final lamp design.
CHAPTER 7:  
CHAIR FOR CRISTINA

Concept

The concept for the chair project arose from a specific use. Cristina, a sixth grade teacher, needed a chair for grading student work that promoted better posture during long grading sessions. This constraint led to an investigation of how chairs function and a questioning of the traditional concepts of comfort and ergonomics. Architectural critic Reynor Banham famously stated that “all ‘well-designed’ chairs are both uncomfortable and inconvenient” (Cranz 1998, 137). This project aimed to challenge that notion by designing a chair that had conceptual rigor and met modern ergonomic standards.

Galen Cranz’ essential 1998 monograph The Chair is a look at the historical origins of chairs, their social and stylistic influence, and the effects of historical and modernist chair design on the human body. Cranz posits that “in the home, in the office, and in schools, social purposes override physiological comfort when it comes to chair design” (64). According to Cranz, chairs are important social signifiers, denoting both social status and taste. He suggests that this arises from a strictly Westernized view of the chair as a throne, comparing the seated to a king or god (34). This close link between chair and status is evident in contemporary culture on the prominent online chair retailer sit4life.com, where, in addition to categories such as “Stools” and “Task Chairs”, they categorize some chairs as “Management & Executive” (sit4life.com, 2014).

There is not, however, a link between the physiological needs of humans and the chair as it exists now. Cranz maintains that chairs “did not originate as a straightforward response to the bends at our ankles, knees and hips” (23). A look to other cultures and
their working and leisure positions demonstrates the Western cultural influence inherent in the chair; in many other cultures, from India to China, squatting, standing or even laying down is the primary working position. Similarly, a prone position dominates leisure time in many cultural contexts. Cranz believes that chair sitting is actually dangerous and unhealthy, and cites a number of research articles to that effect (97-101).

From this understanding of a chair as a social construct and a health hazard, a broader idea of chair ergonomics begins to develop. Rather than designing a chair that is comfortable for many hours of sitting, it made more sense to design a chair that promotes shifting and alternate postures and positions. Initially, this meant sitting and standing configurations, but additional research led to two other positions: straddling and what Blade (1974) refers to as “the edge”. This is a seated position at the leading edge of a chair that achieves “a three-point stable contact – edge contact with the buttocks, and two feet spread apart on the ground. This is a stable position yet even leaves the person free to squirm occasionally” (62).

Through a series of conceptual and material iterations, the design evolved into a chair that incorporated a shelf that could be used as a lectern when standing behind the chair, or as a small desk when the chair is straddled backwards (Figure 36). This promotes a series of alternate uses, encouraging movement rather than trying to avoid it entirely.
Despite the evidence that sitting is unhealthy, it was critical to provide a chair that would function well for sitting as well as other positions. Cranz (1998) identifies several “minimum” ergonomic characteristics of any chair, and these became the hard constraints for the chair design (101-105). Those characteristics are outlined in Table 1.

Table 1: Ergonomic characteristics and requirements for the chair.

<table>
<thead>
<tr>
<th>CHARACTERISTIC</th>
<th>REQUIREMENTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seat Not Too High</td>
<td>The seat should be fit to the popliteal height of the sitter, so that the feet can rest squarely on the ground without pressure to the back of the knee. The chair can either be adjustable or fit to the individual.</td>
</tr>
<tr>
<td>Curved Front Rail</td>
<td>The front rail of the seat should curve downward to eliminate pressure points on the backs of the thighs</td>
</tr>
<tr>
<td>Depth and Width = 17”</td>
<td>For most adults, a chair depth and width of 17” is appropriate. These dimensions can be specified to the individual.</td>
</tr>
</tbody>
</table>
**Weight Distributed Through Bones**

The body weight of the sitter should be transferred to the chair through the bones, not the flesh. This primarily means that deeply upholstered chairs are not healthy.

**Space Between Seat and Back**

Continuous seat/back configurations prevent the body from sitting fully upright. Allow at least 6 inches between seat and back for the buttocks.

All chair iterations needed to conform to these basic requirements. Most could be accomplished by fitting the chair to Cristina’s proportions, so all design systems were based on a set of measurements taken off Cristina’s body in a seated position. These dimensions (and therefore the final chair) are specific to Cristina, but could be quickly changed to fit any other individual. In essence, therefore, this project became the design of a bespoke chair system, rather than an individual chair.

**Material Strategy**

Parallel to the investigations into ergonomics, a number of material manufacturing strategies were explored. An initial decision to use a CNC router as the primary manufacturing tool provided helpful material direction to the design.

Investigations into sheet and board stock eventually led to the decision to limit the material to a single sheet of ¾” stock. Another constraint – the router’s inability to make undercut elements – drove the decision to limit milling to a single side. This was partially an effort to control the amount of time required to mill the chair, but also added an interesting challenge to the design.

The final material approach took all these requirements into consideration. The chair would be constructed of layered plywood, secured with glue and using ¼” dowels
to register each layer correctly. In plan, the chair would have three inflection planes – centered in the legs on each side and in the center of the seat. At each plane the milled side of the material would flip. This resulted in five sections of layering, each with a similarly oriented tapering profile (draft angle).

The shape of the chair itself is based on this concept, but also extends it through the use of mesh relaxation algorithms. The basic form of the chair is a series of lofted ellipses defining leg and back locations and set of seat profiles extruded into a solid. The ellipses and seat shapes are located and scaled to reduce the amount of material required to provide a rigid chair. This is achieved through selective thickening and the use of triangular support elements. The various objects are merged, and a triangulated mesh copy is relaxed to the designer’s specifications. The parametric environment allows the designer very precise control over every aspect of the form (Figure 37). The final design was essentially designed in a manual way, by adjusting sliders to find a visually appealing and structurally minimal iteration. This final design was sectioned according to the principles above.

Figure 37: The parametric controls over the chair enabled precise design.
Fabrication

Once the sections were divided, they were reoriented flat onto the XY plane and baked into Rhino. The geometry was used to generate milling paths, and the pieces were cut using a CNC router (Figure 38). Unfortunately, the file cut time was in excess of that available, so a test chair was cut using only the outlines of the sectioned parts. While this version fails to test the visual approach, the ergonomics could be confirmed, as the surfaces touched by people were cut to contour. Once the pieces were cut, the chair was assembled by hand, layered with wood glue and clamped (Figure 39). Lastly, the finished chair was sanded to provide a smooth surface for sitting. The finished chair is essentially a study of the final design, allowing for visual understanding without an intensive time commitment (Figure 40).

Figure 38: The chair was cut using a CNC router.
Figure 39: Chair assembly was performed by hand.

Figure 40: The finished and assembled chair.
CHAPTER 8:
BARN FOR TWO DONKEYS

Site Review and Precedents

The final exploration of parametric tools – the Barn for Two Donkeys - operated at the third level of integration: Parametric Elements. A step in the design process and two elements in the barn were selected for parametric treatment, then integrated into a more conventional design process that allowed for quick formal definitions.

During the initial conceptualization of the thesis, the author was approached with a request for a barn design. From a list of potential projects both real and imaginary, this project was selected as a viable candidate for an experimental parametric treatment because of its relatively small scale, real-world context and limited budget. The client asked for a fully functional barn to house two full-size donkeys and the feedstock and equipment required for their upkeep. They also requested storage for other farm and garden items unrelated to the donkeys. The project scale – approximately 600 square feet total after an initial programming analysis – was approachable within the allotted timeframe, and the simple program meant that more attention could be directed to the parametric elements without jeopardizing the quality of the overall design.

Additionally, barn design and construction is largely an effort of economy and function, not artistic expression. Requiring a practical, buildable design that could be feasibly built within a normal budget range for a barn grounded the project in a realism often ignored in theoretical parametric designs for pavilions, installations or large projects. The additional constraint of using wood framing also provided a helpful
pragmatism to the project; a local builder should be able to build the barn using (primarily) standard framing and sheathing techniques. This eliminated complex steel frames and abstracted panelized surfaces, requiring instead a focus on specific aspects of the building process that lend themselves to a parametric, differentiated approach.

**Parametric Element 01: Siting Evaluations**

The site for the project – the client’s home – is located in Western Massachusetts, in a small rural town of 1,500 people. The 10-acre property is located primarily on an open hillside facing south, with a residence at the crest of the hill. The residence is a single story modernist house with a two-story traditional addition to the east. A large flat roof caps the original house, and is perforated by two south-facing shed clerestories providing light to two bedrooms and a bath. Forest surrounds the house to the north and west, following the property lines to the east. The field to the south is used for agricultural purposes, including hay production and strawberry farming. The client wanted to locate the barn close enough to the house to allow for a water and electricity tie-in, and to offer easy access during winter months. Because the view from the house is one of its primary assets, it was critical to consider viewshed in addition to more practical aspects. This basic limitation led to the selection of two possible siting areas: one to the north of the house, nestled into the trees somewhere along the edge of the rear yard, and another below the knuckle of the hill, partially concealed from sight. While each site offered particular benefits, the rear site was
selected for its proximity and because the client expressed interest in a future in-law addition to the rear of the house that would require road access.

Bundling these two potential programs into one master plan, the design began with a quick sitework plan. A road rising from the existing parking area would run along the north edge of the house to offer access to the rear lot and barn. This required the removal of several trees and gave a barn a minimum setback from the northeast corner of the house.

Based on this location and approach, a series of siting options were explored using a generative genetic algorithm. Located on a digital map of the site, a basic rectangular site of 600 sf was placed a variable distance and angle from the center of the house and rotated up to 360°. The shape of the rectangle could morph to a minimum dimension of 8 feet in either direction to allow for various footprint strategies. The algorithm took into consideration a series of hard constraints, including avoiding sites in or too close to the house, in the viewshed, or in any trees. It was then optimized for a number of criteria, including variation from the primary axis of the house (15° north of east), slope over the site, and distance from the house. Each characteristic was input as an evaluation criterion into an Octopus setup, and controls over site location, shape and rotation were input as ‘genes’. This process followed largely the same procedure as the generative formfinding system used to define the lamp. See Chapter 6 for more information on this process.

Initial Octopus runs resulted in fairly unexpected and less than useful results. For example, early runs did not take property lines into account, and many initial sites were
located outside of the property boundary. An additional hard constraint remedied this mistake. The setup was eventually tweaked to produce a series of ‘expected’ results, occupying the most obvious site locations and in the most obvious orientations. However, at one point a conversation over the value of the trees on the property led to lifting the constraint requiring the barn to avoid all the trees on the site. This produced a series of site options that had not been previously considered, and opened the site substantially to people and animals. Based on the realization that removing, not adding, constraints to the algorithm could produce unexpected and useful results, a series of runs were executed, removing various constraints and criteria to see what new possibilities might arise (Figure 41). While none of the runs produced particularly notable site options, the process of removing constraints did begin a series of discussions of the most critical project requirements, and opened the design field greatly. Additionally, an overlay of the best options from the series of runs shows a concentration of viable options occupying a narrow stand of trees directly north of the house (Figure 42). Although none of the sites were selected exactly as generated by the software, this concentration did prove to be the best location for the barn when siting was considered through a subsequent, more intuitive approach. The generative process then was less a production technique and more an exploration of the site forces at work.
Figure 41: Various run configurations used different sets of constraints and criteria.

Figure 42: Overlaying the various runs reveals a concentration of optimal sites.
Conceptual Development

Once the site location was generally narrowed to its final location, a study of the program led to a series of conceptual diagrams. The program (Table 2) is fairly simple, but there is a notable divide between the programmatic elements related primarily to the donkeys and those related to human activities. Typically in barns, the transition zone between animal and human is fairly thin, manifesting in a single wall or fence. This border was thickened into a gradient conceptually, while still maintaining wholly human and wholly equestrian zones. Additionally, several of the programmed spaces – such as feed storage and rainwater collection – were related to donkeys but required that they be separate from the animals themselves. By locating these zones along a linear gradient, the polarity of the space is maintained, reinforcing behavioral cues for the donkey and providing them with a safe space that is their own. The relationship between the human and equine elements of the barn led to a spectrum diagram (Figure 43), where all the programmatic elements were located on a spectrum between donkeys and humans. This gradient affected the programming of the building as well as the form, at the structural and skin levels.
Table 2: Barn program requirements.

**Barn Program:**

<table>
<thead>
<tr>
<th>Description</th>
<th>Area (sq ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Donkey quarters:</strong></td>
<td>200</td>
</tr>
<tr>
<td>Enclosed on at least 3 sides</td>
<td></td>
</tr>
<tr>
<td>Closed on walled sides to the ground</td>
<td></td>
</tr>
<tr>
<td>Sturdy construction</td>
<td></td>
</tr>
<tr>
<td>Waterproof roof structure</td>
<td></td>
</tr>
<tr>
<td>At least 20-30 sq ft per animal</td>
<td></td>
</tr>
<tr>
<td>Provide year-round ventilation</td>
<td></td>
</tr>
<tr>
<td><strong>Feed storage</strong></td>
<td>75</td>
</tr>
<tr>
<td>Dry</td>
<td></td>
</tr>
<tr>
<td>On ground level, or in loft with easy stair access</td>
<td></td>
</tr>
<tr>
<td>Storage for 3000 lb of hay</td>
<td></td>
</tr>
<tr>
<td><strong>Rainwater collection and storage</strong></td>
<td>140</td>
</tr>
<tr>
<td>Roof collectio</td>
<td>50</td>
</tr>
<tr>
<td>Storage in summer for water for 2 donkeys</td>
<td></td>
</tr>
<tr>
<td>for all days above freezing</td>
<td></td>
</tr>
<tr>
<td><strong>Workbench and tool storage</strong></td>
<td>25</td>
</tr>
<tr>
<td>Storage for medicines, salt licks, halters, tools</td>
<td></td>
</tr>
<tr>
<td>Assorted donkey equipment storage</td>
<td>50</td>
</tr>
<tr>
<td>Cart storage, other</td>
<td></td>
</tr>
<tr>
<td><strong>Lawn tractor storage</strong></td>
<td>50</td>
</tr>
<tr>
<td>Dry, easy access</td>
<td></td>
</tr>
<tr>
<td><strong>Lumber storage</strong></td>
<td>25</td>
</tr>
<tr>
<td>Dry, on racks</td>
<td></td>
</tr>
<tr>
<td><strong>General storage</strong></td>
<td>125</td>
</tr>
<tr>
<td><strong>Total:</strong></td>
<td>600</td>
</tr>
</tbody>
</table>


Figure 43: Diagram placing programmed elements on a spectrum between spaces primarily for donkeys, and those for humans.

Additionally, as the primary activities within the barn related directly to feeding the donkeys and the subsequent waste removal, a similar diagram exploring the digestive cycle of hay and waste (Figure 44) also provided organization to the program. The barn is a physical location for the digestion of plant matter into soil nutrient. Hay from the field is brought in and dried, removing moisture and encasing calories. It is then fed to the donkeys and passes through their digestive system, breaking into glucose and proteins for the animals, and into waste fiber material in their dung. Dung is collected and composted, creating rich humus for fertilizing new plantings. This transition from plant material readily accessible by animals to animal material readily accessible by plants is not a smooth one, but is a gradient punctuated by a series of acts: stacking, feeding, eating, defecating, piling. These punctuations provided focal points or design and action. For example, a dilation in the gradient at the location of the hay could provide increased ventilation, and a narrowing at the point of consumption will create a psychologically safe space for the donkey to eat its food. The gradient manifests both in the surface and the structure of the barn.
Figure 44: Concept diagram placing the barn in the cycle of hay growth and digestion.

Based on these diagrams investigating *punctuated gradient*, a series of massing options that explored the idea of polarity and gradient were explored. These varied from very simple bars to more complex, multi-mass ideas (Figure 45). Based on the requirement that the barn be built using standardized construction methods, no undifferentiated, curvaceous options were explored. From these massings, three were selected as most viable for construction and most formally promising. These were each considered throughout the following design phases, as it was assumed that the simplicity of the project program allowed for various avenues of exploration.
The next step of the design phase explored how a building could exhibit a gradient at volumetric and surface levels. This began with a conceptual modeling of the program as a three-dimensional blob called a *metaball*. Modeled in Grasshopper, a metaball uses a set of points as centers of spherical shapes that carry individual, user-defined charges. Based on their charge and proximity to each other, the shapes bridge, joining into a single shape. The charges can be assigned a multiplier to achieve desired visual effects. In this exploration, each point was located in the center of a programmatic space in a working plan, and the point’s charge was based on the square footage of the programmatic element and a desired ceiling height, which generally coincided with level of activity in each space. The final result (Figure 46) is a pure representation of program by area and activity level. The transitions between programmatic elements are seamless, and the whole object becomes a gradient from one space to the next. This undifferentiated three-dimensional diagram was never considered as a massing, as the shape would prove unfeasibly difficult to construct.
However, the smooth transitions between elements and their spatial relationships to each other were clarified in this process. Additionally, several potential advantages were identified with a sloped transition between surfaces. Namely, a sloped surface could be used to direct otherwise vertical flows. Warm air rising off the donkey quarters could be directed past the hay storage to provide a constant airflow and aid drying, and a sloped eave could be used to collect rainwater into a catchment. Finally, the change in ceiling height can be used to create two atmospheric spaces for the donkeys; a shorter space can provide refuge for eating and sleeping, while a taller space can promote movement and exploration during cooler months.

Figure 46: A metaball model of the building with point charges by programmed area and activity level.
Parametric Element 02: Ruled Roof Surfaces

Taken into an architectonic language, these physical representations of gradient led to an exploration of the ruled surface as a transitional form. Ruled surfaces – those where a straight line on the surface runs through every point on the surface – are a fascinating area of geometry, but have particular relevance to architecture, as their linear description lends them favorably to construction with straight building members. There are many examples of ruled surfaces in architecture, including Antoni Gaudi’s school building at the Sagrada Familia in Barcelona, Spain (Figure 47), and Santiago Calatrava’s Bodegas Ysios in Laguardia, Spain (Figure 48). In the Escuela Sagrada Familia, the structure lies to the inside of the building; a series of wooden beams with ends rising and falling on curved brick walls support a Catalan thin-tile roof. Calatrava’s structure is simultaneously his roof, with large Glulam beams forming the ceiling and roof surfaces. Metal roof panels to the exterior offer protection from the elements. The structural systems on both these projects are the same, using straight beams mounted at varying heights to describe a curve in profile. However, they use two different surfacing methods, and in doing so highlight a challenge with ruled surface construction.
Figure 47: The Escuela Sagrada Familia by Atonio Gaudi uses a ruled surface for its roof.

Figure 48: Santiago Calatrava’s Bodegas Ysios in Laguardia, Spain uses large Glulam beams to create a ruled roof form.
In choosing their surfacing methods – small tiles with a large tolerance and the structural elements themselves – each architect has managed to avoid the issue of deformation in a ruled surface. As a surface is described as a series of straight lines between two sets of points (e.g., joist-top plate connections), each individual section between two curves undergoes a deformation, even when the adjacent ends of the curves are equidistant from each other. This phenomenon can be seen when trying to bend a thin sheet of cardstock between one’s hands. As the bend increases, each edge tends to curve as the material in the center of the sheet pushes outward. Opposite edges can be held straight, but all four edges cannot be straight without creating a fold along the diagonal of the sheet (Figure 49). This deformation is initially plastic, but as the bend angle increases, the resistance to the bend increases as well. Using long, narrow panel shapes that minimize the bend in one direction, such as standing seam roofing, provides a solution, as does minimizing the bend angle overall.
Additionally, when viewed in plan, the introduction of a bend into a flat panel has the unintended effect of changing the projected position of the translated corner (Figure 50). In a construction context, this means that either each panel must be cut or otherwise shaped to fit, or the overall footprint must deform and each joist must be slightly off parallel. In the Escuela Sagrada Familia, Gaudi chose to use a material with a high level of tolerance – the thin tile and its grouted joint – to account for the overall deformation between joists. By allowing the roof surface to form a non-rectangular shape, he allowed his joists to lie parallel to each other. In this case, the roof surface also provides its own support, eliminating the need for a layer of sheathing.
Considering this problem in the context of typical residential construction methodology in the United States is challenging, but precedents exist. Particularly thorough is Happy Box Architecture’s exploration of this issue in their Frank Residence Addition project in Charlotte, North Carolina (Figure 51), a small addition with a series of overlapping, twisted gable roofs. Included in Christopher Beorkrem’s 2013 *Material Strategies in Digital Fabrication*, the designers developed a clear strategy to allow for the use of standardized materials and construction methods (95-99). The process began with the description of the surface as a loft between two straight lines defining the opposite gables of a roof surface. This surface, while ruled, presented the same problems described above; the deformations in the roof shape would prohibit the use of standing seam roofing, as the roof surface edges wouldn’t lie at the edges of the roof as defined. However, by mapping points onto the surface based on their relative distances before deformation, the designers were able to locate exactly where the corners of rectangular sheets would land when deformed. To do this, the architects used a process
called *sphere-mapping*. The process assumes that given a fixed distance between two points, a sphere can be drawn centered on one point, with radius equal to the distance between points, and the second point will lie on the sphere. As long as the second point lies on the sphere, it can move freely while maintaining the original distance between points. When the first point (the sphere center) is located on a surface, the sphere will create curve where it intersects with the surface. The second point can lie anywhere on this curve and maintain its original distance. Applied to architectural design, each of three corners of the standing seam are placed on the surface, and two spheres are drawn, one with radius equal to the shorter dimension, and one equal to the longer dimension. They are intersected with the surface, and where the intersection curves meet, the fourth and final corner of standing seam will land. In the Frank Residence Addition, the entire roof was mapped onto the surface, moving progressively from corner to corner. This method was also applied to the rafters to insure that they were the correct lengths and positioned correctly to accommodate the standing seam. The process was repeated on each side and for each gable roof.
Based on this design and fabrication strategy, the ruled surface was applied to the barn. Early explorations looked at the barn as a series of curves – ridgeline, two eaves and two sills – with ruled surfaces drawn between them (Figure 52). Moving the curves and changing their profiles could quickly generate a wide variety of ruled masses. However, a quick structural evaluation ruled out the idea of any studs far out of plumb, and the ruled surface was essentially limited to the roof structure.
Relating back to the program, the ruled surface was reconsidered as a functional, not decorative, element. The programmatic requirements and spatial relationships described above were modeled in a massing process diagram, utilizing the unruly nature of the ruled surface to advantage building functions (Figure 53). The resulting form – a shifted mass with a partially twisted shed roof resting on a more orthogonal lower level – uses the ruled surface to achieve performative effects, including forcing rising hot air toward the center of the building, collecting runoff near the donkey quarters, and creating a sheltered entry on the southeast corner.
In the Frank Residence precedent, an initial ruled surface was used as a basis for the final mapped surface. However, based on an understanding of the requirements of using a ruled surface, a reverse approach was chosen for the barn. A rectangular surface was folded according to a sphere-mapping, insuring that the final shape would break perfectly into rectangular panels. This process was developed parametrically; three corners of a surface were fixed, and the fourth was rotated around an axis through the adjacent corners. The trajectory of the fourth corner follows a line of intersection between two spheres with centers on the adjacent corners and radii equal to the edge lengths (Figure 54). This process ensures the surface maintains consistent edge lengths, and therefore can be panelized without custom cutting. By using a parametric system, later changes to the dimensions and angles of the barn were propagated through the roof design, eliminating substantial 3D redrafting work.
Figure 54: The two spheres with radii equal to the edge lengths define a path for the adjacent corner.

Once the surface is defined parametrically, the roof was divided perpendicular to the wall top plates to locate the rafter positions. The spacing of the rafters was adjustable, but a standard value of 24 inches on center was selected. The rafters were not parallel to each other, but spaced evenly by distance along the top plates. Initially unintuitive, the placement of these rafters actually complies with standard construction practice. The fact that they are not parallel in plan has no consequences during construction of the roof, but is merely a byproduct of the design. The deformation does shape the building below. Each rafter line was then extruded in two dimensions and notched at the top plates to the full width of the plate. The rafter tail cuts were based on a plumb line off each rafter exactly one foot along the rafter from the top plate, regularizing the unprojected width of the eave. This allows for a consistent width soffit and boards.
The angles for each cut were calculated and used to create two adjustable angle finder tools. Traditional rafter cuts are marked using a 12” speed square; preset marks indicate the cuts required to achieve various slopes. This technology was adapted to create a tool for marking variable rafter cuts, both at the top plate and at the rafter tails. The top plate tool is essentially a rotating disc with a 90° notch for the mark (Figure 55). A fence aligns with the long edge of the rafter, the disc is rotated to the correct angle, and the notch is marked. The angles collected from the rafters were translated to the disc, and a hole was created to receive a peg (or a roofing nail) at each angle. The holes were numbered so the rafters could use a numerical indexing system and proceed linearly from one end to the other. A separate tool was designed to give the angles for the rafter tails (Figure 56). A straight edge is rotated on a fence, with identically indexed holes for pegs at the correct angles. Each rafter would be marked sequentially and would follow the same steps (Table 3). The process is detailed in Figure 57.

Figure 55: The top plate cut tool scribes the correct angles without measurements.
Figure 56: The rafter tail cut tool marks the end cuts.

Table 3: Rafter tails and seats marking and cut process by step.

<table>
<thead>
<tr>
<th>STEP</th>
<th>ACTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>01</td>
<td>MEASURE 1’ ALONG RAFTER FROM BOTTOM</td>
</tr>
<tr>
<td>02</td>
<td>SET SEAT CUT TOOL TO APPROPRIATE ANGLE, AND MARK LOWER SEAT CUT</td>
</tr>
<tr>
<td>03</td>
<td>MARK BOTTOM RAFTER TAIL CUT FROM BOTTOM CORNER USING TOOL</td>
</tr>
<tr>
<td>04</td>
<td>FROM TOP OF THIS MARK, MEASURE A SET LENGTH ALONG RAFTER TOP AND MARK</td>
</tr>
<tr>
<td>05</td>
<td>FROM THIS MARK, MARK TOP RAFTER TAIL CUT USING TOOL</td>
</tr>
<tr>
<td>06</td>
<td>FROM BOTTOM OF THIS MARK, MEASURE AND MARK 1’ ALONG RAFTER LENGTH</td>
</tr>
<tr>
<td>07</td>
<td>SET SEAT CUT TOOL TO THIS MARK, AND MARK UPPER SEAT CUT</td>
</tr>
<tr>
<td>08</td>
<td>CUT ALL MARKS USING A STANDARD CIRCULAR SAW</td>
</tr>
</tbody>
</table>
Figure 57 - Sequence of marks and cuts of a typical rafter.

**Parametric Element 03: Vented Siding**

Parallel to the exploration of ruled surfaces in the roof, a study of siding options was also undertaken. Initially, this was an exploration of the idea of gradient at a surface level. As a starting point, two differently colored materials were used to show the transition from one to the other. Based on standard barn siding methods, a number of siding options were generated quickly using Grasshopper (Figure 58). These varied from pixelated shingles and vertical clapboards to mixed horizontal and vertical siding to board and batten strategies. The board and batten diagram was selected for continued development as it implied a volumetric shift in the surface from an upper to a lower mass.
As the siding was developed further, the board and batten system was abandoned but the concept was maintained; a shift in siding instigates a shift in volume, and vice versa. These early diagrams looked at the boards in a vertical orientation, but as the massing strategy developed, a horizontal transitional moment in the barn was identified. The knuckle of the upper mass where it diverges from the united volume became a location for a punctuated transition from one surface to another. To further separate these surfaces, a board width was chosen for the two masses: 3” for the upper,
diverged volume, and 6” for the lower and combined masses. These widths in multiples allowed for the easy transition from two 3” boards to a single 6” board. Next, a quick exploration into transition strategies led to a system where single 6” boards were cut lengthwise to a specific length and one side was bent outwards, as shown in a concept model in Figure 59. This system allowed for a volumetric transition between non-parallel planes. Additionally, the bending of the boards created an opening behind each, providing an outlet for ventilation.

This system lent itself easily to parameterization. The two surfaces were divided into board-widths and a point was placed at the center of the ventilated area. The lists of boards were filtered into upper and lower board sections, and the lower sections
were left in place. The control points of the upper boards were moved outward based on their proximity to the central point, so that each was bent at a consistent maximum angle. This guaranteed that each board would not be bent beyond its elastic range. The depth of the rip on the 6” board was set to the last set of displaced control points. These distances were rounded to the nearest inch, and compiled into a list. To create this transition, each board would be ripped on a table saw to an indexed length, as listed in Table 4.

Table 4: List of siding cut lengths.

<table>
<thead>
<tr>
<th>BOARD NO.</th>
<th>LENGTH OF CUT (IN)</th>
<th>BOARD NO.</th>
<th>LENGTH OF CUT (IN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>13</td>
<td>19</td>
<td>62</td>
</tr>
<tr>
<td>1</td>
<td>16</td>
<td>20</td>
<td>64</td>
</tr>
<tr>
<td>2</td>
<td>19</td>
<td>21</td>
<td>66</td>
</tr>
<tr>
<td>3</td>
<td>22</td>
<td>22</td>
<td>67</td>
</tr>
<tr>
<td>4</td>
<td>25</td>
<td>23</td>
<td>68</td>
</tr>
<tr>
<td>5</td>
<td>28</td>
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</tr>
<tr>
<td>6</td>
<td>31</td>
<td>25</td>
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</tr>
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<td>7</td>
<td>34</td>
<td>26</td>
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</tr>
<tr>
<td>8</td>
<td>36</td>
<td>27</td>
<td>71</td>
</tr>
<tr>
<td>9</td>
<td>39</td>
<td>28</td>
<td>72</td>
</tr>
<tr>
<td>10</td>
<td>42</td>
<td>29</td>
<td>72</td>
</tr>
<tr>
<td>11</td>
<td>44</td>
<td>30</td>
<td>72</td>
</tr>
<tr>
<td>12</td>
<td>47</td>
<td>31</td>
<td>71</td>
</tr>
<tr>
<td>13</td>
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<td>71</td>
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<tr>
<td>14</td>
<td>52</td>
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<td>70</td>
</tr>
<tr>
<td>15</td>
<td>54</td>
<td>34</td>
<td>69</td>
</tr>
<tr>
<td>16</td>
<td>56</td>
<td>35</td>
<td>68</td>
</tr>
<tr>
<td>17</td>
<td>58</td>
<td>36</td>
<td>67</td>
</tr>
<tr>
<td>18</td>
<td>60</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

After ripping, each board would be nailed into place, starting at the fixed end.

Nailer blocks would be attached to the studs along the bent boards, starting at the center. The central blocks would be measured and cut by hand according to a schedule,
then nailed in place. Each other block would then be slid into contact with the bent board and nailed. The board would then be face-nailed to the blocks. Finally, a second stud and face board would be nailed to the support stud, concealing the blocks from the inside to avoid them being jostled loose during barn operations. Figure 60 shows this nailing system, and Figure 61 diagrams the entire cutting and assembly process.

Figure 60: Nailing diagram for blocks and boards in siding system.
Final Design

The final design of the site and barn met all the programmatic requirements set out at the beginning of the project, utilizing parametric design to achieve several specific effects in the building. The addition of a new road and retaining wall at the northeast corner of the house provides vehicular access to the rear lot. The building is usually approached from this road (Figure 62). The road bends to the north at the barn, passing into the woods to a compost heap to allow for easy seasonal removal of compost. To the north of the barn, the road forks and is bermed to 3’ up the north wall. This raises the ground level to a mere 6’ below the upper floor, providing easy access to the hayloft from a standard truck bed. To the south of the barn, a grass lot leads to the primary entrance to the donkey paddocks, where donkeys can stand with full view to the major
approaches to their area. The paddocks wrap around the west side of the building, extending to the western property line and north into the woods. This area, mostly woody and bare, meets the restrictive digestive requirements for a standard donkey, while providing year round pockets of sun and shade (Figure 63). Donkeys enter the barn along this west side, while the primary entrance for humans is located at the southeast corner.

Figure 62: The view of the barn from the approach along the road.
The barn is sided in a combination of 6” and 3” horizontal board siding, left unfinished to reference the historical tone of American barns as well as the cedar clapboard of the residence itself. The west elevation (Figure 64) presents first to the user, with a pedestrian entrance to the south and a vehicular-width door on the north corner. Two flap windows fold down below the cantilevered second story overhang, opening the building to the airflow during fair seasons. Above, two matching glazed windows have rotated outward with the upper mass. An additional window above the vehicular door provides natural light to the hayloft area. Along the south side, more first-story flap windows and second story glazed units provide air and light, and give the
donkeys a visual connection to the approach from inside their quarters (Figure 65). At the southwest corner the rainwater collection tanks shelter against the building and a drainpipe delivers runoff. At the base of the two water tanks, a trough provides clean water to the animals on demand with a float valve (Figure 66). Rounding to the west, two large sliding doors access the donkey quarters and two staggered windows provide lighting to the combined northern volume (Figure 67). The upper volume follows the lower on this side, but a 3” cantilever provides visual separation as well as a slight recess for the donkey doors. From this elevation, the shape of the roof is visible, hinting at the functions it serves. Finally, passing out of the paddock to the north, the bermed entrance to the second loft dominates the façade. Here the entire wall is composed of 6” boards, and reads as a continuous whole.

Figure 64: The barn’s east elevation is the first visible upon approach.
Figure 65: The south elevation provides light and openings to the donkeys.

Figure 66: The rainwater collection system provides warm-season water to the donkeys on demand.
Figure 67: The west elevation provides access to the donkey quarters.

Returning to the southeast and entering the barn from the southeast entrance, the visitor is immediately presented with a view of the donkey quarters, with a 4’ partition separating the animals from a hallway along the east wall (Figure 68). This hallway runs under an upper walkway that ends at the threshold to the donkey’s area, opening to a taller space to prevent the animals from hitting their heads. Two doors provide access to the donkey quarters. These two doors and the stall dimensions hint at a future use; the barn could be used to house horses, which require separate stalls of a particular dimension. Across the stall, an interior watering trough is fed by the rainwater collection tanks.
Either by walking down the hallway or through the vehicular entry to the north, one enters the human-focused area of the barn. A stairway to the upstairs hugs the south wall, and under it a workbench provides a location for fixing bridles, preparing medicines or repairing cart tires. The workbench also provides storage for tools and supplies. On the opposite wall, a series of racks provide storage for lumber, and between are parked a riding lawnmower, wheelbarrow and various other farm and garden equipment. The open hallway provides visual and aural continuity between the spaces, but the partitions separating the spaces provide a clear boundary.
Climbing the stairs to the second story, the user enters the hayloft, a tall, well-lit space (Figure 69). To the north, the hayloft door opens to a view of the forest, and ahead to the east a large horizontal window opens to the road and the approach to the building. The southern wall opens at the head of the stairs to a lofted walkway. This vantage point above the donkey quarters provides a temporary storage for small amounts of hay, and acts as a drop-off point for hay bales headed to the animals. Overhead the rafters form a shifting rhythm, and at the bend at the start of the hall the moiré effect of the vented siding creates a horizontal, diffuse light and a consistent airflow (Figure 70).

Figure 69: The second floor plan of the barn.
Figure 70: The view of the vented siding from the hayloft.
Each of the three design projects – lamp, chair and barn – approached parametric integration from a different angle, and as a result the way in which parametric tools were incorporated into the design process differed greatly. However, there were a number of similarities between approaches. Noting these similarities helps to identify several universal strategies for successful parametric integration.

**Parametric Process in Design of the Light Skipper Lamp**

In this first project, an early and well-clarified concept led to a parametric definition with a clear purpose and overall goal, although the details of the lamp geometry were left to the algorithm. Generative formfinding tools are quite complex and require an extensive setup, but in this case the simplicity and clarity of design lent itself well to a more involved definition. After the concept was clarified and the lamp form selected, parametric tools were invoked to form the lamp in both its general shape and specific surfacing. This process, while extensive, allowed for the generation and evaluation of a very large number of lamps, and provided careful control over the proportions and dimensional ranges of each individual. The steps outlined in Table 5 were taken sequentially during the design process. As noted, parametric tools were invoked at Step 05, and used until the beginning of the initial fabrication setup at Step 14. The final production steps were all manual.
Table 5: Process steps in design and manufacture of the lampshade. Parametric steps = **bold**, manual steps = *italics*.

<table>
<thead>
<tr>
<th>STEP</th>
<th>ACTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>01</td>
<td>SELECT A CONCEPT</td>
</tr>
<tr>
<td>02</td>
<td>PICK A LAMP TYPOLOGY TO BEST MATCH CONCEPT</td>
</tr>
<tr>
<td>03</td>
<td>SELECT A MATERIAL AND SYSTEM APPROACH</td>
</tr>
<tr>
<td>04</td>
<td>DEFINE THE QUALITIES OF AN OPTIMAL DESIGN</td>
</tr>
<tr>
<td>05</td>
<td>DEFINE BASIC CHARACTERISTICS OF THE LAMP</td>
</tr>
<tr>
<td>06</td>
<td>SET DESIRED RANGES FOR CHARACTERISTICS</td>
</tr>
<tr>
<td>07</td>
<td>DEFINE AND ISOLATE GOVERNING CRITERIA FOR FORMFINDING ALGORITHM</td>
</tr>
<tr>
<td>08</td>
<td>RUN OPTIMIZATION ALGORITHM</td>
</tr>
<tr>
<td>09</td>
<td>CORRECT FOR UNDESIRED RESULTS</td>
</tr>
<tr>
<td>10</td>
<td>RE-RUN OPTIMIZATION</td>
</tr>
<tr>
<td>11</td>
<td>SELECT A WINNER FROM THE FIELD</td>
</tr>
<tr>
<td>12</td>
<td>SLICE LAMP INTO SECTIONS</td>
</tr>
<tr>
<td>13</td>
<td>REORIENT SLICES FLAT ONTO XY PLANE</td>
</tr>
<tr>
<td>14</td>
<td>TRANSLATE GEOMETRY TO MILLING PATHS</td>
</tr>
<tr>
<td>15</td>
<td>MILL FROM FOAM</td>
</tr>
<tr>
<td>16</td>
<td><strong>REASSEMBLE MOLD INTO THREE PARTS AND REASSEMBLE</strong></td>
</tr>
<tr>
<td>17</td>
<td><strong>APPLY ADHESIVE AND PAPER TO MOLD, LET DRY, AND REMOVE FROM MOLD</strong></td>
</tr>
</tbody>
</table>
Parametric Process in the Design of the Chair for Cristina

The second project looked at a more manual description process, but in many ways required a more intensive use of Grasshopper. Again, a concept – non-standard ergonomics – and a material approach – single-sided milling – led to a design and production strategy. However, this project saw early setbacks, as the initial design concepts proved fruitless after defining parametrically. Each chair design was drawn digitally using completely parametric tools, so each required a substantial time investment, with little or no usable results. As David Celento (2010) notes, “the precision involved in manufacturing software (accurate to thousandths of an inch) can be limiting to free architectural design exploration” (63). The flexibility of parametric tools lies in the production of complex and various options, but the initial definition process is fairly cumbersome. As such, the investment of time, particularly for non-generic projects, must be justified by a rigorous investigation of the concept.

Once a robust concept was selected, description and production proceeded relatively quickly, and the flexibility the parametric definition offered proved useful. Micro-adjustments to the chair were performed easily without compromising any previous or future actions, and a series of relaxation algorithms were used to smooth the edges of the chair, providing an undifferentiated form. Fabrication also benefitted from the ability to slice the chair into even-thickness sections. Table 6 shows the sequential steps in the design of the final concept. Again, parametric tools were
implemented after the concept and material approaches were clarified. The final assembly steps were also performed manually.

Table 6: Process steps in design and manufacture of the chair. Parametric steps = **bold**, manual steps = *italics*.

<table>
<thead>
<tr>
<th>STEP</th>
<th>ACTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>01</td>
<td><strong>RESEARCH ERGONOMICS AND PRECEDENTS</strong></td>
</tr>
<tr>
<td>02</td>
<td>SELECT A CONCEPT</td>
</tr>
<tr>
<td>03</td>
<td>PICK A CHAIR TYPOLOGY</td>
</tr>
<tr>
<td>04</td>
<td>SELECT A MATERIAL AND CONSTRUCTION SYSTEM APPROACH</td>
</tr>
<tr>
<td>05</td>
<td><strong>DEFINE THE CHAIR’S CHARACTERISTICS</strong></td>
</tr>
<tr>
<td>06</td>
<td>ADJUST TO THE DESIRED SHAPE</td>
</tr>
<tr>
<td>07</td>
<td><strong>INPUT CRISTINA’S DIMENSIONS</strong></td>
</tr>
<tr>
<td>08</td>
<td><strong>RUN MESH RELAXATION ALGORITHM</strong></td>
</tr>
<tr>
<td>09</td>
<td><strong>SLICE CHAIR INTO SECTIONS</strong></td>
</tr>
<tr>
<td>10</td>
<td><strong>REORIENT SLICES FLAT ONTO XY PLANE</strong></td>
</tr>
<tr>
<td>11</td>
<td><strong>TRANSLATE GEOMETRY TO MILLING PATHS</strong></td>
</tr>
<tr>
<td>12</td>
<td><strong>MILL FROM PLYWOOD</strong></td>
</tr>
<tr>
<td>13</td>
<td><strong>APPLY GLUE, ASSEMBLE AND CLAMP</strong></td>
</tr>
</tbody>
</table>

**Parametric Process in the Design of the Barn for Two Donkeys**

The final project utilized the lessons learned in the first two projects successfully, and integration of parametrics was smooth. Each discrete parametric element was developed as a concept prior to parameterization, and integrated into the project as a
whole. This top-down, systems-level organization insured that no time was wasted on unproductive definitions. The first element was a site exploration, and a simplified approach was quickly identified and executed, with the understanding that the product was not tied to production. As a theoretical exploration, mistakes and unexpected outcomes were embraced as potential steps forward. This flexibility freed the exploration greatly and countered the inertial effects of parametric design. As a series of potential sites were selected, a clearer understanding of the site requirements arose from the process. In this way, the process became the result.

The second element, the roof, arose from both a conceptual exploration and a set of programmatic needs. The ability to define the surface quickly, accurately and with a wide range of adjustment lent flexibility to the digital model and allowed for multiple corrections to form and plan. Once the shape was defined, the parametric tools were used to divide the shape into roof panels and extract rafter lines. Finally, the numerical data stored in the parametric model was used to create a series of fabrication tools that automatically adjusted to changes in the original model. The digital component of fabrication was greatly simplified as a result.

The final parametric element – the vented siding – also followed a similar trajectory, developed in response to a clear concept and material strategy. While initial parametric studies were not used in the final design, they proved useful as quick research projects on the road to a siding system. Unlike all the other projects in this thesis, the majority of the definition for the siding was devoted not to production but to representation. As the fabrication strategy only required a list of rip lengths, the
production output was available almost immediately in the parametric model. However, the ability to test a series of designs visually is critical to making an informed decision as an architect. In this way, having an incrementally, adjustable visual model provided the information necessary to pick a particular variation. All the process steps used in the design of the barn are listed in Table 7.

Table 7: Process steps in design and construction of the barn. Parametric steps = bold, manual steps = italics.

<table>
<thead>
<tr>
<th>STEP</th>
<th>ACTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>01</td>
<td>IDENTIFY AND DIGEST THE PROGRAM AND SITE</td>
</tr>
<tr>
<td>02</td>
<td>DEFINE THE GOVERNING CRITERIA OF AN OPTIMAL SITE</td>
</tr>
<tr>
<td>03</td>
<td>DEFINE THE PARAMETERS CONTROLLING SITE</td>
</tr>
<tr>
<td>04</td>
<td>SET DESIRED RANGES FOR PARAMETERS</td>
</tr>
<tr>
<td>05</td>
<td>RUN OPTIMIZATION FOR GOVERNING CRITERIA</td>
</tr>
<tr>
<td>06</td>
<td>ADJUST CRITERIA, RANGES AND PARAMETERS</td>
</tr>
<tr>
<td>07</td>
<td>RE-RUN OPTIMIZATION</td>
</tr>
<tr>
<td>08</td>
<td>ASSOCIATE THE PROGRAMMATIC REQUIREMENTS WITH FORMAL MOVES</td>
</tr>
<tr>
<td>09</td>
<td>DESCRIBE MASSING PROCESS DIAGRAM</td>
</tr>
<tr>
<td>10</td>
<td>ISOLATE ROOF FOR PARAMETRIC TREATMENT</td>
</tr>
<tr>
<td>11</td>
<td>SHAPE ROOF ACCORDING TO CONSTRUCTION REQUIREMENTS</td>
</tr>
<tr>
<td>12</td>
<td>TAKE SECTION LINES AT RAFTERS</td>
</tr>
<tr>
<td>13</td>
<td>EXTRUDE RAFTERS TO DESIRED DEPTH</td>
</tr>
</tbody>
</table>
Summary of Parametric Steps

While the steps for integrating parametric tools were different in each project, there were several similarities worth noting. Firstly, the integration of parametric tools
was usually most successful when applied after the development of a complete concept. Particularly in projects that used parametric tools for finished production, the introduction of parametrics too early tended to result in gridlock. While parametrics do offer a stunning level of flexibility in a completed definition, the slow process of creating that definition make these tools clumsy for idea generation and clarification.

Secondly, parametrics were almost always used continuously from their initial integration until some sort of digital fabrication. While digital fabrication was interrupted in each case for various reasons, this continuity from design description to fabrication belies a strength of parametric tools. Parametrics transition very smoothly into digital fabrication, as definitions can embody massive amounts of data that can be translated directly into moves for a fabrication tool.

Lastly and in some contradiction to the previous point, it is often productive to abandon parametrics in later stages of a design project if the final construction will not be digitally fabricated. Standard digital drawing techniques are extremely quick, and once a parametric design element is fixed, a project can become more agile in an implicit environment. This approach was used in the modeling of the barn siding; once the final form was set, the Grasshopper forms were ‘baked’ into Rhino and manipulated implicitly to conform to the roof form and for the generation of drawings. This process was much quicker than a fully parametric system and allowed for rapid progression of the project.
CHAPTER 10:
FOCUS 02: AGENCY IN DESIGN

A common concern with parametric design centers on the fact that individual elements are not drawn manually, and that therefore the level of designer agency is potentially lessened. Willis and Woodward (2010) write,

Parametric modeling software “automatically” generates forms based on data input by the operator of the computer. Such a process requires that the architect give up control of form to a computer-generated algorithm to regain control in areas where it has been lost to other professions. We would argue that, for the process to be successful, the architect’s active participation is necessary; there is nothing “automatic” about it. (203)

While the control over each element is certainly less with a parametric system, the control over the whole is far greater than if each element is drawn separately. The ability of parametrics to create incremental differentiation over a surface or mass is its strength. The relative scale and proportion of each element is controlled, but not its actual scale and proportion. This systems-level control is not intuitive for designers or builders, but in some ways parallels management practices. The intent of a set of components can be coordinated to achieve a desired result, but each part is left to perform its task individually. As a result, the designer must relocate their creative energy away from individual elements and toward the assembled whole. Conceptually, this is an enriching process; rather than forcing a number of elements to conform, the designer can simply tell the program what they want and the elements must comply. In terms of the design process, this generally focuses the agency of the designer to the early phases of design, and requires them – like a good management executive – to
relinquish control later in the project. In each of the projects executed here, the dialogue over designer agency was a critical element of the design process.

**Agency in the Lamp Project**

Designer agency in the Light Skipper Lamp project is isolated to the initial definition phase (concept development, basic characteristics, criteria to solve for, and value ranges) and to the final selection process. This contrasts with a typical design process, in which intuitive decisions are made throughout the schematic and design development stages. Designers may find this relocation of agency disconcerting, but all the decisions made in an equivalent design process for a similar object – from material to shape to surface pattern – are present in the parametric definition. Surprisingly, during the review process, one critic found the limited number of sliders to be a sign that control of the design was limited. However, the linking of various elements and parameters means that the control is in fact present, but not visible.

On a conceptual level, there were perhaps no more options considered as in an equivalent, conventional design process. The value of an optimization design approach lies in the *exhaustive exploration of a single approach*, and in the flexible and fast testing of multiple related versions.

**Agency in the Chair Project**

The design process of the chair was almost entirely manual. Sketching dialogued with modeling in Grasshopper, and each influenced the final design. As modeling
systems, parametric tools offer some limitations and advantages. The mathematical, parametric definition of an object is somewhat less fluid than modeling in implicit software such as Rhinoceros, and it can also be time-consuming. Whereas a manual design process allows for complete directional shifts at any time, parametric systems may require a near-complete rewrite to effect an equivalent shift. Gains later in the process can make up for this initial clumsiness. And unlike a formfinding approach, a fully parametric definition allows a massive degree of design autonomy and flexibility. A designer can adjust parametric values to get a precise level of control over the final product. While at some point Grasshopper has structural limitations, the ability to use plugins and scripting expands the range of design possibility to a fantastic degree.

**Designer Agency in the Barn Project**

Whereas the first two projects were fully parametric, the Barn for Two Donkeys was mainly a manual project with interspersed parametric elements. The control over where and how these elements were integrated guaranteed complete designer autonomy. As an example, an early design phase looked at the addition of a parametric rainwater collection system, but this entire component was abandoned both as unwieldy and unnecessary. This project truly saw the level of integration recommended by Jason Payne in *From Control to Design*: “indexing incidentally, just to get the job done” (Ferré and Sakamoto 2008, 222). Each aspect of the project that was selected for parametric treatment was enhanced and simplified by the process. The control over each element as well as their fabrication was controlled to the fullest extent through
parametrics. In this project Grasshopper was truly a tool in the hands of the designer, and in no way controlled the process.
CHAPTER 11:  
FOCUS 03 – LABOR AND PARAMETRIC DESIGN

Labor and Parametrics

Parametric tools such as Grasshopper are essentially automation tools. They perform constant, repetitive actions at a tremendous rate, allowing for incremental control over the dimensions, relationships and properties of objects. When automation was introduced to manufacturing during the Industrial Revolution, there was a shift away from family-run, craft-based jobs toward new, skilled forms of labor. These new jobs arose necessarily from the demands of a more complex manufacturing process. However, many people mourned the loss of craft and its associated diversity as mechanized labor crowded out more expensive, smaller enterprise. Kiel Moe (2010) also notes,

> digression in the required knowledge and skill required of human labor... diminishes the value and wage of labor itself. One of its more acute effects is the displacement of work. This results in structural unemployment... (162)

While structural unemployment is just that – part of the labor structure – it takes a personal, cultural and economic toll.

This pattern is paralleled in home construction as well. Major home manufacturing companies such as Horton and Pulte Homes have mechanized and automated many aspects of the construction process, relocating construction from the jobsite to a factory. Some companies such as Germany’s Baufritz have automated the construction of whole wall and roof assemblies, down to window and door installation. Panels fabricated offsite are framed into a mostly complete house in a single day (BTI
This relocation of construction jobs to a factory floor is a challenge for smaller conventional contractors, who cannot compete with the efficiencies gained through this automation. While on a macroeconomic scale jobs are being created, this transfers ownership (and therefore profits) to larger organizations that can afford the initial outlay for the required infrastructure. Willis and Woodward (2010) note, “the demise of the skilled craftsperson is one instance in the ongoing transfer of economic and political power from those who work with their hands to the privileged class of ‘symbolic analysts’ who manipulate information” (195). While these prefabricated homes do not account for a significant portion of the home construction market, they may portend things to come.

In the architectural design industry, the advent of CAD software was seen as a similar challenge to the work performed by draftsmen before the wide introduction of computers. The ability to produce duplicate drawings quickly and easily led to a restructuring of many aspects of the architectural practice, from billing and project management to integration with engineers and trades. But perhaps most importantly, the ability to create many drawings quickly allowed architects to shift precious time from documentation to design. As a result, for any given project, a wider range of potential options can be explored in a shorter amount of time with a smaller budget. Rather than eliminating jobs, this technological advancement increased production and grew more skilled labor positions. However, economic forces forced draftsmen who could not adapt out of the market. Additionally, Willis and Woodward (2010) express
concern over the tendency of gains in efficiency “to make ‘ordinary’ buildings even cheaper and simpler” (192).

This trend of a new technology eliminating some jobs and creating others can also be applied to parametric design and digital fabrication. David Celento (2010) notes, the capabilities now provided by furniture system designers, sustainability consultants, construction managers, and engineers of all stripes have become so advanced that Martin Simpson of Arup suggests that architects may eventually become unnecessary – except, perhaps, as exterior stylists. (57)

While it is possible that some design positions will be eliminated by the automation of processes with parametric design, the creation of jobs in this sector may outweigh the losses. Willis and Woodward (2010) insist that “using computers to aid the designer’s decision-making, rather than to simply represent designs worked out by other methods, is unquestionably a step forward for the profession” (190). BIM tools in particular have resulted in the creation of a large number of specialized positions in architecture and consulting firms. The BIM process – while potentially very productive and efficient – is also fairly complex, and requires specialization to understand fully at a very large scale.

Additionally, Robert A. M. Stern contends in the introduction to Peggi Deamer’s Building (in) the Future (2010) that current digital trends seem to be trending toward the ancient model of the master builder. He writes that,

The expanding technology of computer software and digital fabrication techniques promises to make it possible for architects to regain their proper and responsible role not only with regard to design but also in the generation of construction documents and fabrication of the finished product. (15)
From this perspective, the role of the architect will expand with the introduction of digital tools, and certainly in some cases this is true. Firms such as SITU in New York City that incorporate both design and fabrication arms are becoming increasingly common, claiming the design and construction of complex elements for the architect.

While the effects of parametric tools on design are largely positive, digital fabrication seems to have a different effect on construction labor. Fabrication is not at the center of this paper, but it is the logical result of a design process, and therefore demands consideration. Architecture in the parametric age increasingly aims to remove the hand of the builder from the final result. The current interest in process and fabrication has led to extensive research into complete digital fabrication processes, where labor is excluded almost entirely from the construction process. This research includes 3D printing of entire structures by companies such as Contour Craftings. Their additive concrete printing system can print the walls for a house in a matter of days in a fully automated process. Similarly, researchers headed by Gramazio and Kohler at the ETH in Zurich seek to assemble complex curvature brick walls with 6-axis robots, and even flying drones. These technologies, if implemented on a large scale, will certainly result in a shift in the arrangement of labor. Again, skilled craft is at risk, while technologically advanced jobs will grow.

While a capitalist economy demands progress and growth, there is an accumulation of knowledge and experience in the skilled trades that is invaluable. Most technological revolutions abandon this knowledge in favor of profit and progress, but a more careful and incremental adoption of progress can allow for a smoother transition,
maintaining the existing workforce (and the experience it retains) and creating new jobs. Kiel Moe (2010) writes that “a hybrid system that still [relies] upon the technician’s intelligence and skill, while automating certain aspects of production [is] a more socially and economically sustainable endeavor” (162). In the context of these projects, therefore, an active attempt was made to modify and redirect common manual fabrication methods to achieve the desired digital result. Each project tries to use a common fabrication or assembly method, redirected toward a more digital result.

**Lamp**

The manufacturing process for the lamp – CNC-machining of a mold for manual construction – references the Akari light sculptures of Isamu Noguchi (Figure 71). To construct Noguchi’s lamps, light-gauge wire is wrapped around a removable armature, then paper is applied to each resulting facet, and the armature is removed. All the lamps are made manually from start to finish, but they use a predetermined mold to regularize the shape. The Light-Skipper Lamp proposes a similar process. Each shade would be manufactured individually by hand, while conforming to a predetermined CNC-cut mold. While replicable and standardized, each iteration of the lamp shows the hand of the manufacturer, adding character and texture to the shade. This process both prioritizes the importance of manual labor in the construction process, and lends a uniquely handmade nature to the shade.
Chair

The chair project accepts the limitations of traditional manufacturing processes in creating customized, contoured parts, and relies heavily on digital fabrication to create a repeatable, bespoke process. However, assembly and finishing are manual processes that cannot be eliminated from construction. Unlike a factory line chair, each individual unit is different, and therefore requires a slightly different assembly process. The prevalence of individual, manual labor in other bespoke processes such as tailoring and custom car fabrication belie the ability of the human brain to adapt to micro-changes in process far faster and more fluidly than any machine. This ensures the hand of labor in fabrication.
Barn

The first parametric element – siting the building – was a completely design-oriented process, and therefore had little consequence for labor. Both the built parametric elements use simple tools or measurements as their primary strategy. The tools developed for marking and cutting rafter seat and tail cuts are based on universal construction tools, and their use would differ little from these traditional methods. Additionally, the inclusion of a numbered indexing system greatly reduces the chance of human error during construction, meaning that almost anyone could cut and assemble this complex roof. Similarly, the siding system leaves little room for error; the series of measurements are merely ripped into the boards prior to nailing to the building, and a single line of central backer blocks locates the boards to reduce the chance of error. Rather than prefabricating elements offsite, these tools allow for onsite construction and assembly, maintaining existing positions and labor hierarchies while producing a highly complex result in a low-budget context.
CHAPTER 12: CONCLUSION

Parametric digital design is a powerful tool in an architect's repertoire. The definition of objects by mathematical relationship rather than visual appearance allows for very precise, flexible and repeatable design, and for coordinated differentiation between elements. It also provides a direct link to methods of digital fabrication. This thesis investigated the historical roots of parametric design, including the origins and the philosophy that underpin a parametric approach. Parametric design was considered critically, both as a system and as a formal strategy. Consideration was also given to the Parametricist movement, which espouses an intensive use of abstract geometric ornament as part of contemporary architecture. From this review, the importance of conceptual drivers for design was illustrated in three precedents, which all used parametric tools to further a concept.

These precedents and the prior research led to the categorization of parametric design into five levels of integration, and the three most intensive levels were assigned projects to test different integrated processes. A lamp project explored generative parametric formfinding, using parametric controls to optimize for three criteria that enhanced the desired visual effect. Next, a chair design explored a fully parametric definition process as a way of providing customizable and ergonomically advanced seating. Finally, a barn design explored the integration of parametric tools at an architectural scale. A first project explored siting the building according to a generative parametric algorithm, and two parametric architectural elements were integrated into the barn as a response to conceptual drivers.
The conclusion of the three projects led to a retrospective consideration of process, agency and labor in parametric design and fabrication. In general, it was found that projects were most successful when concept preceded parametric consideration. Additionally, parametric tools pair exceedingly well with digital fabrication, so considering fabrication strategy early in the design process streamlined later stages and enabled more complete design realizations. Execution of these projects also revealed interesting realizations regarding designer agency in parametric processes. While many architects see parametric tools as a relinquishing of control, it was found that while each individual element was beyond designer control, the overall organization of elements provided excellent management-level control. A top-down approach mirrors architectural practice; architects are generalists and coordinators with broad knowledge in many fields, working to manage specialized engineers and trade workers. Extending this managerial approach to design is potentially productive and time-saving. Finally, a consideration of the effects of parametric design and digital fabrication on labor – both in the design office and in the field – concluded that while some repetitive, drafting-type jobs may eventually disappear, the inclusion of digital design and fabrication will create specialized and high-paying jobs. However, the expertise in the field now can be preserved through the adaptation of non-parametric processes to a parametric result. In the various projects, common manual techniques were used to fabricate the various designs, providing a transitional space for the less digitally able.
Final Remarks

This thesis began two years ago as a polemic; as a designer, I believed that parametric tools were the answer to most architectural questions, so I set out to design a framework for applying them to any scenario. What followed was a much more critical look into what it means for something to be parametric. Parametrics are inherently embedded into a design; because they take data from ‘site’ information, they are inextricably linked to that site. This means that a good definition is extremely specific to a project. Moreover, the definition itself has the ability to embody a concept, which is also specific to a project. Just as a concept must arise from the project description and narrative, so too should parametric design engage a specific context. This seems to be a marker of quality parametric design; it is highly specific to a project and arises as a result of the needs of that project. Those needs can be structural or performative, or – as the Parametricists and Moussavi would argue – ornamental. According to Willis and Woodward (2010), “parametric modeling remains best suited to organize technical knowledge related to a building’s geometry or construction system” (189). Acknowledging this subordination of parametrics to concept demands that projects face a critical examination prior to integrating parametric tools. In some cases parametrics should be abandoned for the benefit of the project. But when the project calls for a parametric approach, these tools can provide a powerful and precise answer to a multitude of design questions.


